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# **Pre-Flight Testing of Thermoelectric Quartz Crystal Microbalances (TQCM) for Midcourse Space Experiment (MSX) Spacecraft**

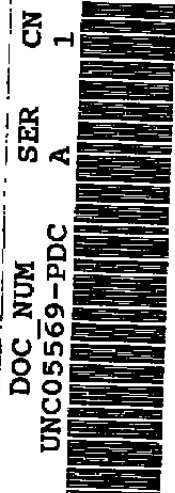
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**February 1994**

**Final Report for Period December 1992 – May 1993**

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**ARNOLD ENGINEERING DEVELOPMENT CENTER  
ARNOLD AIR FORCE BASE, TENNESSEE  
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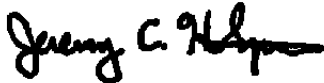
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## APPROVAL STATEMENT

This report has been reviewed and approved.



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FOR THE COMMANDER



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13. ABSTRACT (Maximum 200 words)  Testing of six Midcourse Space Experiment (MSX) satellite thermoelectric quartz crystal microbalances (TQCM) was completed. These will be used to monitor contamination at various locations on the spacecraft. The tests included a 3-week drift test, power on/off tests; temperature cycling of TQCM crystals, mounting base, and flight electronics box; and deposition of carbon dioxide gas. The data obtained will be used for analyzing MSX satellite flight contamination data.				
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## **PREFACE**

The work reported herein was performed by the Arnold Engineering Development Center (AEDC), Air Force Materiel Command (AFMC) under Program Element 921Y01 at the request of the Johns Hopkins University/Applied Physics Laboratory (JHU/APL), Laurel, MD. The manager of this project was Dr. Manuel Uy of JHU/APL. Mr. Trung Le and Lt. Jeremy Holtgrave were the AEDC Air Force project managers. Test results were obtained by Calspan Corporation, AEDC Operations, support contractor for the Aerospace Flight Dynamics Testing effort at AEDC, AFMC, Arnold Air Force Base, TN. The tests were performed in a small cryovacuum test facility developed specifically for this purpose from December 15, 1992 through May 10, 1993, under AEDC Project Number 0229.

The authors wish to thank B. W. Hobbs and W. E. Johnson for their help in setting up and operating the test facility.

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## **1.0 INTRODUCTION**

The Midcourse Space Experiment (MSX) satellite will contain several contamination experiments. One of these experiments involves monitoring the deposition of contaminants at four locations around the satellite with thermoelectric quartz crystal microbalances (TQCM). Operational characterization tests were required for the four flight and two spare TQCMs and for the flight electronics box (FEB) which controls and monitors all of the onboard quartz crystal microbalances. These TQCM characterization tests were conducted at AEDC, and this report documents the results.

The specific tests to which the FEB and TQCMs were subjected were: (1) thermal vacuum test to assure operation throughout the anticipated environmental envelope, along with condensing CO<sub>2</sub> on the crystals to assure proper response; (2) cycle TQCM crystal temperatures while holding TQCM mounting base and FEB temperatures constant; (3) cycle TQCM mounting base temperature while holding crystal and FEB temperatures constant; (4) cycle FEB temperature while holding crystal and TQCM mounting base temperatures constant; (5) constant temperature tests to determine long-term stability; and (6) monitoring of the FEB and flight cable outgassing in the ambient temperature upper chamber.

During the testing, occasions arose when some of the flight hardware had to be removed for repair or for use at other locations. This necessitated that the test setup be modified, and in some cases, substitution of TQCMs occurred. Data presented in this report are confined to the test setups which best represent each type of characterization.

This report does not include all the data obtained during the tests, but describes the particulars of each test phase and presents some typical results from each phase. The equipment used to accomplish the test objectives is also discussed. All the data from the test program are contained in a data package released to JHU/APL on June 21, 1993. Requests for data package copies should be addressed to JHU/APL, Laurel, MD 20707.

## **2.0 APPARATUS**

### **2.1 TEST FACILITY**

The MSX flight components were tested under vacuum and at various temperatures. Figure 1 shows the test facility used to accomplish these tests. The facility consists of a lower section which was a cryopump where the QCMs were mounted, an upper section that housed the FEB, a turbomolecular pump to help maintain vacuum conditions, and an isolation valve between the turbomolecular pump and chamber. The interior layout of the test chamber is also shown schematically in Figs. 2, 3, and 4.

The cryogenic core of this facility is a Leybold-Heraeus RPK-10000 cryopump capable of producing first-stage temperatures on the order of 50 K with a heat input of 90 w and second-stage temperatures on the order of 10 K with a heat input of 6.3 w. The normally installed pump baffle and cryopanel were removed and replaced with a heat-sink mount for the cryogenic quartz crystal microbalance (CQCM) and a modified baffle plate covered with a 10-layer aluminized Mylar® shield. A heat sink for mounting the TQCMs was attached to the first stage and is discussed in more detail in Section 2.2.1.

Part of the thermal vacuum test required that CO<sub>2</sub> gas be condensed on the TQCM crystals to be sure they were responding properly. A stainless steel tube with holes drilled in it was installed in front of the TQCMs to furnish the gas for this deposit. Gas was supplied from a bottle through a commercial leak valve.

The upper part of the test chamber was an aluminum cylinder with feedthrough tubes in the side that could pass liquid nitrogen or water coolant into and out of the chamber. The temperature-controlled aluminum base plate for the FEB was mounted in this upper chamber. The FEB base is discussed in greater detail in Section 2.2.2.

Pressure in the cryopump enclosure was measured with a tubulated Bayard-Alpert ionization gauge and was on the order of  $2 \times 10^{-8}$  torr. This pressure was more representative of that which existed between the radiation shield and the outer shell of the cryopump than that which existed near the QCMs inside the radiation shield. Based on the temperature difference between the glass envelope of the Bayard-Alpert gauge and the environment inside the radiation shield, the pressure near the QCMs was probably on the order of  $5 \times 10^{-9}$  torr. Pressure in the upper chamber, as measured by a Bayard-Alpert gauge, was on the order of  $1 \times 10^{-7}$  torr.

To minimize the effects of any possible power interruptions on tests (particularly on the long-term stability tests), the vacuum pumping and data handling systems were powered from a 50-kw uninterruptible power supply. If a power failure occurred, the isolation valve between the vacuum pump and the chamber would automatically close. To further protect the flight hardware from contamination, a circuit was added to close the isolation valve if turbomolecular pump rotation speed fell below its normal level.

## **2.2 TEMPERATURE CONTROL OF FLIGHT EQUIPMENT**

### **2.2.1 TQCM Mounting Base Temperature Control**

Test requirements dictated that TQCM housing temperatures be controlled at values ranging from 76 to 343 K. These temperatures were maintained by mounting the TQCMs to a 0.25-in.-

thick aluminum plate heat sink whose temperature could be controlled at any value within the required range. This control was accomplished by balancing heat supplied to the heat-sink plate against a constant amount of cooling. The heat sink was fastened to a second 0.25-in.-thick aluminum plate through four, 0.5-in.-diam by 1.0-in.-long stainless steel stand-offs that gave a degree of isolation because of their length-to-diameter ratio. This second plate was in turn fastened to the first stage of the cryopump cold head with the same screws that held down the radiation shield (See Fig. 3). The heat sink to which the TQCMs were attached had four 120-ohm foil heaters epoxied to it which would supply about 150 w of heat. The partial isolation of the heat sink from the cold base furnished by the stainless steel stand-offs allowed the heat-sink temperature to be varied in relation to the temperature of the cold head by the heaters without overheating the cryopump. Silicon diode temperature sensors were mounted to the TQCM heat sink to monitor and control its temperature. The TQCM heat-sink silicon diode used for temperature readout was connected to a Lakeshore temperature monitor. A QCM Research model 1819 QCM controller and a DC power amplifier were used to power the heaters and maintain set temperatures of the heat sink. With the dual requirements of a heat-sink upper temperature capability of about 340 K and steady-state heat rejection to the cryopump not to exceed about 90 w, stand-off size limitations dictated that the rate of heating or cooling of the heat sink be limited to about 1 K/min. A schematic of the plate heater system is shown in Fig. 5.

Since the tested TQCMs were flight units, a safety device was included in the heat-sink heating system to protect them from overheating in case of a temperature control circuit malfunction. This safety device was a thermal fuse with an opening temperature slightly higher than the maximum test temperature anticipated inserted in the heater power supply cable in series with the heaters. The fuse was then mounted on the heat-sink plate with low outgassing epoxy. If the heat-sink temperature reached the fuse's opening value, power to the heaters would be disconnected.

### 2.2.2 FEB Mounting Base Temperature Control

Temperature control of the FEB mounting base was similar to that of the TQCM base. Again, two aluminum plates separated by six, 0.5-in.-diam by 1.0-in.-long stainless steel stand-offs were used. The cold plate had aluminum tubing welded to it that was connected to a feedthrough in the side of the chamber. Either liquid nitrogen or water could be circulated through the tubing to cool the cold plate, depending on the requirements of the particular test. Approximately 250 w of heat was supplied to the base plate by eight, 180-ohm foil heaters. Silicon diode temperature sensors were used to monitor and control the base plate temperature, and a second channel in the model 1819 QCM controller, along with a second DC power amplifier, furnished power and control for the heaters. The base plate temperature was also

read by the Lakeshore temperature monitor. A second thermal fuse protection circuit was incorporated into the FEB heater system. Maximum heating and cooling rates for the FEB were limited to about 0.75 K/min.

### **2.2.3 CQCM Mounting Base Temperature Control**

Checkout of the FEB operation required that a CQCM be used to exercise that portion of the electronics. The S/N 890 CQCM which was tested previously at AEDC has been designated as the backup unit for the MSX and was used during this test for checkout of the FEB. This unit was mounted to the second stage of the cryopump cold head. The CQCM base was allowed to follow the temperature of the cold head with no heat input from the attached foil heater.

## **2.3 TEST ARTICLE**

The QCMs, the FEB, and the cable tested in this program were flight hardware; therefore, precautions were taken to protect these components from contamination or damage. Clean room gloves were worn anytime a component was handled. Also, when a component was removed from or installed in the chamber, it was cleaned with reagent-grade ethyl alcohol. To protect the FEB from possible damage by static discharge, all personnel likely to come into contact with the FEB or the chamber when the FEB was installed wore a static discharge wrist strap.

### **2.3.1 Thermoelectric Quartz Crystal Microbalance (TQCM)**

The tested TQCMs were Mark 10 models manufactured by QCM Research, Laguna Beach, CA. These units use a dual quartz crystal-controlled oscillator setup, one a sense crystal and the other a reference crystal, to help minimize temperature sensitivity. These TQCMs operate at a frequency of 15 MHz, and they have an internal platinum resistance temperature detector (RTD) to monitor the crystal temperature. They also have an internal Peltier thermoelectric device to heat or cool the crystal so that temperature differences of  $\pm 70^{\circ}\text{C}$ , in relation to their base temperature, can be obtained. The six TQCMs tested had serial numbers (S/N) from 1 through 6.

The TQCMs were attached to the temperature-controlled heat sink with screws tapped into the heat sink. In order to match the mounting technique to be used on the MSX spacecraft, no washers or gasket material was used. The attaching screws were torqued down to 10 in.-lb with a torque wrench.

### **2.3.2 Cryogenic Quartz Crystal Microbalance (CQCM)**

The CQCM used to check out the FEB was a Mark 16 model from QCM Research, S/N 890. The Mark 16 is also a dual-crystal device which oscillates at 10 MHz.

The CQCM was attached to an aluminum holder with screws and spring-type washers, with the screws tightened to compress the washers fully. The holder was in turn fastened to the mounting base with screws and spring-type washers, and the screws were torqued down to 10 in.-lb with a torque wrench. The CQCM was open to the chamber with no protection from the chamber environment.

### **2.3.3 Flight Electronics Box (FEB)**

The FEB is designed to operate four TQCMs and one CQCM. The FEB controls the temperatures of the QCM crystals and furnishes readouts of all the pertinent operating parameters. For these tests, the FEB was the prime data acquisition system. The FEB is discussed further in Section 2.4.3.

The FEB was secured to its mounting plate with spring-type washers and screws torqued to 20 in.-lb. Two wires connected the FEB case to the wall of the test chamber which was in turn connected to a common ground with all the instrumentation.

## **2.4 TEST INSTRUMENTATION**

### **2.4.1 Computer/Instrument Systems**

The computer instrument system (Fig. 6) consists of four input subsystem units plus a central data assembly computer and a data storage computer. The four input units are: (1) the QCM flight electronics system with the Flight Electronics Box (FEB) with its Ground Support Electronics (GSE) computer, (2) the data logger, (3) the silicon diode temperature readout, and (4) the plate temperature controller. The data assembly computer combines the data from the input units into one common data file. The data files from the data assembly computer are sent to a personal computer (PC) for storage and access by the data reduction computers via an ethernet computer network.

### **2.4.2 Data Assembly Computer**

The data assembly computer consists of a Digital Equipment LSI-11 microcomputer that communicates over RS232 serial lines with the other subsystems. The data assembly computer has storage buffers to receive the transmission from all four input subsystems. When a

transmission is sent by the data logger, it is received, then FEB/GSE diagnostic data are taken, followed by the latest buffer values for the plate temperature controller and the silicon diode temperature readouts. The data from these sources are parsed and combined into one file, then transmitted for storage on the data storage PC for ethernet access and data reduction. In addition, the files are stored on the LSI-11 as backup. The data storage interval is determined by the log interval set in the data logger.

### 2.4.3 QCM Flight Electronics System

The heart of the QCM flight electronics system (Fig. 7) is the FEB. The FEB operates four TQCMs and one CQCM. The FEB was mounted on a plate in the upper portion of the chamber. The flight cables were used between the FEB and the QCMs in the bottom portion of the chamber with one exception. The Manganin portion of the CQCM cable was not used. Instead, a short adapter pigtail was used to connect the CQCM to the flight cable.

The Ground Support Electronics (GSE) computer was mounted outside the chamber and connected to the FEB by an adapter cable and chamber feedthrough connector. The FEB received commands from the GSE computer and transmitted its data to the GSE computer. To automate the temperature cycles of the QCMs, a cycle PC was used to emulate the keyboard of the GSE and give the commands at the desired times. Data passed from the FEB, through the GSE, through the cycle PC, to the data assembly computer. In addition, the FEB data were also stored on floppy disk by the GSE computer.

Power for the FEB passed from a 28-VDC power supply through a switch box and into the chamber to the FEB using locally fabricated cables. The switch box was installed to apply and remove the 28-VDC power suddenly, removing the chance of an undesirable slow voltage ramp. A series resistor (0.247 ohm) in the switch box was used to monitor the current supplied to the FEB. The FEB supply voltage was measured at the output of the switch box. Both the FEB voltage and current were recorded by the data logger.

Power interlocks were built into the switch box. The first was to protect the FEB from slow application of voltage. If the 120-VAC or 28-VDC power went off and came back on, the switch box would trip and wait for a manual reset before power was reapplied to the FEB. The second interlock was to protect the FEB if the chamber pressure increased into the corona region. The data logger monitored the chamber pressure ion gauge and tripped a relay in the switch box if the chamber pressure rose above a preset value.

#### **2.4.4 Data Logger System**

A Kaye Instruments Digi 4 Plus data logger was used to measure the chamber housekeeping data, the FEB current and voltage, and the data for the two spare TQCMs not connected to the FEB (Fig. 8). The data logger output was sent to the data assembly computer at intervals selected on the front panel of the data logger. The log interval varied between 1 and 3 minutes.

The spare TQCMs were supplied with 10-VDC oscillator power and 0.1-mA platinum resistor excitation. The Peltier crystal coolers of the spare TQCMs were not powered. Instead, the crystals were allowed to follow the TQCM heat-sink temperature.

A breakout box was used to connect the TQCM parameters to the data logger. The oscillator current was measured by monitoring the voltage drop across a 100-ohm series resistor, and the oscillator voltage was measured at the breakout box. The oscillator frequency was obtained by measuring the voltage output of frequency-to-voltage (F/V) converters. The F/V converters were run with a scale factor of 1.0 V/kHz, except when contaminating gas was deposited on the TQCM crystals; the scale factor was then 0.1 V/kHz. The 250-ohm platinum RTDs in the TQCM crystal packs were wired in a 4-wire configuration and were read in millivolts by the data logger.

#### **2.4.5 TQCM Crystal Cycle Programs**

The proprietary GSE computer program by QCM Research was modified to take commands from the serial port in addition to the keyboard and to transmit the data screen to the serial port in addition to the monitor. This program modification allowed the cycle PC to send commands to the GSE computer and to receive the FEB data from the GSE computer.

A program was written for the crystal cycle computer to communicate with the GSE computer. The program input a cycle table of the desired crystal set points and dwell times. Using this cycle table, the cycle PC sent commands to the FEB through the GSE computer. The cycle PC displayed a mimic of the GSE computer data screen. In addition, the cycle PC parsed the FEB data and transmitted it to the data assembly computer.

#### **2.4.6 Mounting Base Cycle Program**

The mounting base cycle program input a table of the desired set points for each plate: temperature, temperature rate, and dwell time. The cycle computer sent the proper commands

to the model 1819 controller to go to the first set point, then after the proper time had elapsed, the cycle computer commanded the model 1819 controller to go to the next set point, etc. The program also input the controller data, parsed the data, and sent the data to the data assembly computer. The program allowed the different mounting bases to be commanded to different temperatures and at different rates.

#### 2.4.7 Instrumentation Error Analysis

##### 2.4.7.1 Silicon Diode Temperature Sensors

The Lakeshore DT471 temperature sensors had a specified uncertainty of  $\pm 1.5$  K or 1.5-percent of the temperature reading, whichever was greater. The Lakeshore silicon diode temperature readout used for excitation and display had specifications that produced insignificant errors in comparison with the sensor. A check was made of the temperature sensors by dipping them in liquid nitrogen at 740 torr, and then in an ice bath. Results are shown in the following table.

Sensor	Sensor at 77.2 K	Difference	Sensor at 273.2 K	Difference
001	77.0 K	-0.2 K	273.2 K	0 K
002	79.69 K	-0.5 K	271.6 K	-1.6 K
003	76.41 K	-0.8 K	271.1 K	-2.1 K
004	76.36 K	-0.8 K	270.7 K	-2.5 K
005	76.58 K	-0.6 K	271.2 K	-2.0 K
006	76.89 K	-0.3 K	272.4 K	-0.8 K
007	76.78 K	-0.4 K	273.0 K	-0.2 K
008	76.63 K	-0.6 K	271.1 K	-2.1 K

The temperature sensors were all within the quoted specifications.

A major potential source of error with temperature sensors is from poor thermal contact. Differences up to 10 K have been observed. To reduce the error due to poor thermal contact, all of the important silicon diodes were mounted with spring-loaded pressure mounts using low vapor-pressure organic vacuum grease between the object and the sensor. To reduce the conduction of the lead wire, a length of 32 AWG phosphor bronze lead wires was attached to the sensor. Tests comparing the temperatures using multiple types of sensors on the same item indicate that this sensor mounting method holds the silicon diode temperature within a fraction of a degree of the measured item. Sensors 7 and 8, being for reference only, were taped to the top radiation shield of the chamber. This method produced unknown thermal contact errors that varied with how well the tape held the sensor in contact with the radiation shield. Normally, the two sensors agreed within one degree, but on occasions differences of 10 K were observed. With the exception of temperature sensors 7 and 8, the total temperature uncertainty is the greater of 1.5 percent of the reading, or 1.5 K.

#### **2.4.7.2 FEB Voltage and Current**

The Kaye Instruments data logger had a specified voltage input accuracy of 0.006 percent of the reading, plus 2  $\mu$ V, plus one count, a count being defined as the full-scale voltage divided by 65,000. The FEB supply voltage had a voltage divider on the data logger input to scale the voltages into a range acceptable to the data logger. This divider was calibrated to better than 1 percent, giving a potential error of 0.3 V. The lead wires leading into the chamber had a measured resistance less than 0.1 ohm. This contributed an error in the measured FEB supply voltage that varied with current. This lead wire error varied from less than 0.02 V at 0.2 amp to 0.2 V at 2.0 amp. The total FEB voltage uncertainty is 0.5 V.

The FEB current measurement was limited by the calibration of the series resistor used to monitor the current. This resistor was calibrated in place to within 1 percent, giving a total current uncertainty of 1 percent.

#### **2.4.7.3 FEB Acquired Data**

The FEB processed its own data and transmitted it digitally to the data assembly computer. The FEB data acquisition has been discussed in the MSX Critical Design Review documentation and will be only briefly mentioned here.

The TQCM frequencies were measured by the FEB to a resolution of 0.5 Hz. A significant degradation during this test came from noise picked up by the TQCM to FEB signal cables. Normally, a  $\pm 1$ -Hz scatter was observed in the frequency, with spikes of as much as  $\pm 4$  Hz.

The FEB measured the TQCM crystal temperature with 0.25 K resolution. A stated accuracy of  $\pm 0.86$  K was given in the MSX Critical Design Review. The platinum resistor temperature sensor is located between the Peltier heater/cooler and the crystal pack. When the crystal is being heated or cooled, the crystal temperature will lag the platinum resistor temperature sensor by an amount varying with the heating and cooling rate. This value is difficult to estimate, but could be on the order of several degrees Kelvin.

### **3.0 PROCEDURE**

The testing of the TQCMs and FEB was broken into six phases to determine system response to different imposed conditions. These phases were: (1) thermal vacuum, (2) TQCM crystal temperature cycling, (3) TQCM mounting base temperature cycling, (4) FEB base temperature cycling, (5) 21-day continuous operation of entire system with all temperatures held constant, and (6) monitoring of outgassing from the FEB and flight cable in the upper chamber.

During testing, test article changes caused five different equipment orientation versions to be used. In some versions, tests were repeated because different TQCMs were involved as prime units and backup units. (The first TQCM change was necessitated because S/N 2 and 6 Peltier units stopped working.) The FEB would handle only four TQCM units, and six units were involved in the tests, with the spares being monitored by AEDC instrumentation. Not all tests involved six units, and one test (version 3) did not involve the FEB. These different configuration versions are listed in Table 1. The data shown in this report are from only one of the hardware setups for which that particular type of data were obtained, and are from the most recent test where possible.

#### **3.1 THERMAL VACUUM TESTS**

The thermal vacuum test consisted of exposing the TQCMs and FEB to low environmental pressure and then cycling the temperatures of the mounting bases to be sure that all the systems continued to operate. Included as parts of this test were performing on-off cycles of the power to the FEB and condensing CO<sub>2</sub> gas on the TQCM crystals.

The thermal vacuum test was the first test after initial installation of the flight hardware. When the chamber was first pumped down, the chamber pressure gauge indicated that a larger than normal amount of outgassing was present. After some preliminary exercising of the TQCMs and FEB, the flight cable was removed from the chamber and returned to JHU/APL for vacuum bake-out. The cable was reinstalled after bake-out, and a more normal pumpdown of the chamber was accomplished.

The temperature cycling of the bases consisted of ramping the TQCM base between  $-90^{\circ}$  and  $40^{\circ}\text{C}$  and the FEB base between  $-29^{\circ}$  and  $66^{\circ}\text{C}$ . Five full cycles were performed, and the temperature was allowed to stabilize at the end points for 4 hr before continuing the next ramp. The Peltier units of the TQCMs were not operated during the cycle test.

The FEB power on-off tests were performed at three different TQCM and FEB mounting base temperatures: TQCMs  $-195^{\circ}\text{C}$  and FEB  $-34^{\circ}\text{C}$  with power on and off at 5-min intervals; TQCMs  $-90^{\circ}\text{C}$  and FEB  $-29^{\circ}\text{C}$  with power on and off at 15-min intervals; and TQCMs  $45^{\circ}\text{C}$  and FEB  $66^{\circ}\text{C}$  with power on and off at 10-min intervals.

Condensation of  $\text{CO}_2$  gas on all of the TQCM crystals was accomplished by cooling the TQCM base to  $-195^{\circ}\text{C}$  and bleeding in the gas through a tube that faced the crystals. After the gas had been condensed, a thermogravimetric analysis (TGA) was performed on all the TQCMs by warming the base at  $1.0^{\circ}\text{C}/\text{min}$  to evaporate the  $\text{CO}_2$ .

### 3.2 TQCM CRYSTAL TEMPERATURE CYCLING

The temperature-induced frequency characteristics of the TQCM crystals must be known if these effects are to be separated from deposited mass effects. To gain a knowledge of these effects, the TQCM crystals were cycled from  $-70^{\circ}$  to  $60^{\circ}\text{C}$  while the temperatures of the TQCM base and the FEB base were held constant.

Tests were run with all of the crystal temperatures cycled 5 times at  $2.5^{\circ}\text{C}/\text{min}$  while the FEB base temperature was  $20^{\circ}\text{C}$  and the TQCM base temperature was  $-40^{\circ}\text{C}$ . Temperatures at the end points were maintained constant for 1 hr before beginning the next change. This cycle test was repeated with a temperature rate of change of  $0.8^{\circ}\text{C}/\text{min}$ .

Crystal temperatures were cycled in other tests with the FEB temperature at  $20^{\circ}\text{C}$  and TQCM base temperatures of  $-25^{\circ}$ ,  $0^{\circ}$ , and  $25^{\circ}\text{C}$ . The cycle rate was  $2.5^{\circ}\text{C}/\text{min}$  for 2 cycles, and end-point temperatures were maintained constant for 1 hr.

### 3.3 TQCM BASE TEMPERATURE CYCLING

The TQCMs possess the ability to hold their crystal temperatures constant while their base temperatures may be changing. Tests were conducted to determine to what extent base temperature affected TQCM frequency when the crystals were at constant temperatures. These tests consisted of cycling the TQCM base temperature one time from  $-10^{\circ}$  to  $-60^{\circ}\text{C}$  at each of the constant values of crystal temperatures of  $-60^{\circ}$ ,  $-50^{\circ}$ ,  $-40^{\circ}$ ,  $-25^{\circ}$ ,  $0^{\circ}$ , and  $60^{\circ}\text{C}$ . The FEB base temperature was constant at  $20^{\circ}\text{C}$ , and the dwell time at the end points was 1 hr.

A second test was run holding the S/N 1, 3, 4, and 5 TQCM crystal temperatures at  $-50^{\circ}\text{C}$  while the TQCM base temperature was stepped upward from one constant temperature to another. These base temperatures were  $-40^{\circ}$ ,  $-30^{\circ}$ ,  $-20^{\circ}$ ,  $-10^{\circ}$ ,  $0^{\circ}$ , and  $20^{\circ}\text{C}$ . Dwell time at each step was 4 hr.

### **3.4 FEB BASE TEMPERATURE CYCLING**

The control and monitoring of the TQCMs rest with the FEB. To determine if FEB temperature influenced TQCM frequency response, the FEB base temperature was cycled 3 times from  $-25^{\circ}$  to  $50^{\circ}\text{C}$  while the TQCM base temperature was held constant at  $-40^{\circ}\text{C}$  and S/N 2, 3, and 6 TQCM crystal temperatures were held constant at  $-50^{\circ}\text{C}$ . The end-point dwell times were 2 hr.

### **3.5 CONTINUOUS OPERATION**

The MSX mission will require that the operation of the TQCMs and FEB not be susceptible to changes with time when no mass is being deposited. To get an idea of how variable the frequency output from the system was with time, a 21-day continuous or drift test was conducted with TQCM S/Ns 1, 3, 4, and 5. All the temperatures of the components were held constant; the TQCM crystals were held at  $-50^{\circ}\text{C}$ , the TQCM base was held at  $-40^{\circ}\text{C}$ , and the FEB base was held at  $20^{\circ}\text{C}$ . Data points were taken at 3-min intervals during the test.

During the first drift test, TQCM S/N 3 had a continuous frequency increase, and subsequent heating of the TQCM crystals indicated that S/N 3 had picked up a mass deposit that probably came from the upper chamber through a cutout in the top radiation shield. Therefore, a second drift test of 28 days was performed that only involved TQCM S/Ns 3 and 4. The timing of the start of the second test was such that the FEB (which was the main data acquisition interface) was not available, so the test was conducted with AEDC instrumentation and with the radiation shield cutout taped closed. Data points were again taken at 3-min intervals, and all the temperatures were held at the same values used in the first drift test.

A third drift test of only 3 days' duration was conducted with TQCM S/Ns 2, 3, and 6. The FEB was used in this test, and all test conditions were the same as the two previous drift tests.

### **3.6 FEB AND FLIGHT CABLE MONITORING**

At one point, the FEB was removed from the chamber to replace an electronics component. When the FEB was returned for reinstallation, TQCM S/N 5 was moved into the upper

chamber and mounted on a bracket attached to the chamber wall. The FEB and most of the flight cable were also located in the upper chamber. This TQCM could then monitor the evolution of any material condensing on its crystal. The TQCM mounting bracket was not cooled; therefore, the TQCM's crystal could be cooled only as far as its Peltier unit would take it below room temperature. Figure 9 is a photograph of this installation. Before beginning the next test series, the temperature of the crystal in TQCM S/N 5 was set to  $-30^{\circ}\text{C}$  and allowed to collect material for about 17 hr. At the end of the collection period, an attempt was made to do a TGA of the material.

Next, both the FEB and flight cable were removed from the chamber so they could be used in integration work being done at Utah State University. Upon their return, they were reinstalled in the chamber for additional tests. TQCM S/N 5 remained in the upper chamber for the next series of tests. When the chamber was pumped down, the chamber pressure gauge indicated the presence of a larger than normal amount of outgassing. TQCM S/N 5's crystal was cooled to  $-30^{\circ}\text{C}$  to condense material from the upper chamber, and after a collection period of about 3 hr, a TGA of accumulated material was attempted. After 2 days of continuous pumping, the chamber pressure improved considerably, and the S/N 5 TQCM mass accumulation rate was greatly reduced. A successful TGA was then performed on the condensed material.

## **4.0 RESULTS AND DISCUSSION**

### **4.1 DATA PRESENTATION**

Within each hardware setup version, the tests were conducted in the order that best used the test time available. The data curves presented here are organized by test type, with all data from a particular type included in one set of curves, regardless of when the data were obtained. For reference, Table 2 lists all of the tests conducted and gives the date when each was run and which configuration version was involved. A short description of each test condition is also included.

The data curves presented in this report are those selected to best represent each TQCM's response to various stimuli. The curves were generated on a PC using IDL software produced by Research Systems, Inc. Table 2 catalogs all of the plot files that were produced using data from all the various tests. These plots were all contained in the data package previously released to JHU/APL.

Many of the graphs are shown with elapsed time as the independent variable. Elapsed time is measured in hours from 12:00 a.m., January 1, 1993.

## 4.2 THERMAL VACUUM TESTS

### 4.2.1 Power On-Off Tests

Figure 10 shows FEB power on-off results from the test with a TQCM base temperature of  $-195^{\circ}\text{C}$  and an FEB temperature of  $-34^{\circ}\text{C}$ . All of the TQCMs restarted each time when power was restored, but there were transients experienced in the frequency readouts. The Peltier units of the FEB-controlled TQCMs were operated at this temperature, and only S/N 5 would function.

The FEB power on-off test was also run for a TQCM base temperature of  $-90^{\circ}\text{C}$  and an FEB base temperature of  $-29^{\circ}\text{C}$ . All of the TQCMs restarted, but there was again some transient behavior. The Peltier units all worked at this temperature. Similar results were obtained for the FEB power on-off test with a TQCM base temperature of  $45^{\circ}\text{C}$  and an FEB base temperature of  $66^{\circ}\text{C}$ .

### 4.2.2 CO<sub>2</sub> Condensation

Results from the CO<sub>2</sub> condensation and TGA experiment are given in Figs. 11 and 12. (In Fig. 11, elapsed time up to 206.6 hr is the deposit phase. The TGA phase begins after 206.6 hr.) The TQCM base temperature was  $-195^{\circ}\text{C}$ . In Fig. 11, all of the TQCMs showed a positive frequency increase from the CO<sub>2</sub> deposit. Figure 11 also indicates that some of the TQCMs may have ceased oscillation from apparent overload. With continuous deposit, the frequency counter in the FEB reads a positive value until it reaches 32 kHz, then it resets to zero to begin counting positive values again. Sometimes it was difficult to tell if a TQCM had quit oscillating or had just reset to zero. A TGA was performed on each of the TQCMs after the deposit was completed, and the results are shown in Fig. 12. The TQCMs which had a zero level frequency after the deposit phase returned to positive values of frequency at different crystal temperatures. Again, it is difficult to tell if oscillation had ceased or not. It appears that S/N 2 did not stop, S/N 5 did stop, and S/Ns 3 and 6 are questionable. The TQCM temperatures had to be increased using the TQCM mounting base heaters because the Peltier units did not function at this temperature (the lone exception was S/N 5, which did function).

### 4.2.3 Temperature Cycling of TQCM Base and FEB Base

The frequency responses obtained when the temperatures of the TQCM and FEB bases were cycled are shown in Fig. 13. All of the QCMs continued to operate for all the cycles. The TQCM base was cycled from  $-90^{\circ}$  to  $40^{\circ}\text{C}$ , and the FEB base was cycled from  $-29^{\circ}$

to 66°C. The end-point temperatures were maintained for 4 hr before changing to the next value. The Peltier units of the TQCMs were not operated for these cycles.

### 4.3 TQCM CRYSTAL TEMPERATURE CYCLING

Figure 14 shows frequency responses of the TQCMs when the crystal temperatures were cycled from  $-70^{\circ}\text{C}$  to  $60^{\circ}\text{C}$  at  $2.5^{\circ}\text{C}/\text{min}$  with the FEB base temperature maintained at  $20^{\circ}\text{C}$  and the TQCM base temperature at  $-40^{\circ}\text{C}$ . There is considerable variation of frequency with crystal temperature, and a noticeable difference exists between the heating and cooling portions of the curves. The frequencies while heating are greater than those while cooling, except for S/N 2. S/N 2 shows larger values while cooling. The 1-hr wait at the end points also produced large frequency changes without appreciable changes in indicated crystal temperatures. When this cycle test was repeated with a temperature rate of change of  $0.8^{\circ}\text{C}/\text{min}$ , only small differences in frequency response from those in Fig. 14 were evident.

The same crystal temperature cycles were performed at other values of TQCM base temperature. Figure 15 shows the results of these cycles for TQCM base temperatures of  $-25^{\circ}$ ,  $0^{\circ}$ , and  $25^{\circ}\text{C}$ . The cycle rate was again  $2.5^{\circ}\text{C}/\text{min}$ , and the FEB base temperature was  $20^{\circ}\text{C}$ . The same types of frequency responses were obtained for these base temperatures as with the  $-40^{\circ}\text{C}$  value, but there were some shifts in the overall envelope. Also, because of the limit of temperature differential that the Peltier units could hold ( $\pm 70^{\circ}\text{C}$ ), the crystal temperatures could not be maintained at their low value ( $-70^{\circ}\text{C}$ ) when the base temperature was at its high value ( $25^{\circ}\text{C}$ ).

### 4.4 TQCM BASE TEMPERATURE CYCLING

Figure 16 shows the frequency responses of the TQCMs when the TQCM base was cycled from  $-10^{\circ}$  to  $-60^{\circ}\text{C}$  at each of the constant values of crystal temperatures of  $-60^{\circ}$ ,  $-50^{\circ}$ ,  $-40^{\circ}$ ,  $-25^{\circ}$ ,  $0^{\circ}$ , and  $60^{\circ}\text{C}$ . Each of the TQCMs shows a small frequency variation with base temperature, but the largest variation is with crystal temperature.

Frequency responses from the test in which the TQCM base temperature was stepped positively from one value to another while the crystal temperatures were held at  $-50^{\circ}\text{C}$  are shown in Fig. 17. The frequency variations shown in Fig. 17 are of the same magnitude as those exhibited in Fig. 16.

#### 4.5 FEB BASE TEMPERATURE CYCLING

Figure 18 gives the TQCM frequency variations for the FEB base temperature cycling test. Only three of the TQCMs were included in this test: S/Ns 2, 3, and 6. Of these, only S/N 6 showed any appreciable frequency variation, and that was small.

#### 4.6 CONTINUOUS OPERATION

Figure 19 shows the temperature history of the TQCM crystals, the FEB base, and the TQCM base during the 21-day drift test. The frequency responses of all of the QCMs from various drift tests are shown in Fig. 20. Included in Fig. 20 are least-squares linear regression curve fits to the data for comparison. The early part of the 21-day drift test (21-day drift test: Figs. 20a, c, e, f, and h) shows more frequency variation than does the later part. In Fig. 20c, S/N 3 had a continuous frequency increase for the whole test because of mass pickup from the upper chamber through a radiation shield cutout. Figure 20d shows S/N 3 response in the 28-day drift test performed with AEDC instrumentation and with the radiation shield cutout taped closed. There is no evidence of the mass pickup in this second test. (The large spikes in the frequency data at about 2,200 hr elapsed time are caused by noise) Figures 20b and 20g show frequency responses for S/N 2 and 6, respectively, for the abbreviated 3-day drift test. It is not clear whether the small frequency changes shown in these curves are part of the early stage settling time, a real change with time, or a possible mass pickup.

The frequency response of the CQCM for the 21-day drift test is shown in Fig. 20h. The CQCM shows a continuous mass pickup because it was cold enough to cryopump the small amount of air that leaked into the chamber through the O-ring seals, and it was not shielded from the chamber environment.

#### 4.7 FEB AND FLIGHT CABLE MONITORING

Figure 21 indicates the amount of material condensed on TQCM S/N 5 during the first 17 hr of the first test after it was mounted in the upper chamber. The total frequency change over this time was about 50 kHz. At this point, a TGA of the material was attempted, but the TQCM ceased to oscillate when heating was started.

Figure 22 shows the frequency response for about 3 hr of material collection by TQCM S/N 5 during the second test that it was mounted in the upper chamber. This second test was conducted after the FEB and flight cable were returned from Utah State University. The frequency increase during this 3-hr period was about 56 kHz. This is about 6 times the mass pickup rate as that shown in Fig. 21. Also shown in Fig. 22 is an attempt at a TGA

of the material. When heating of the crystal began for the TGA, the TQCM ceased oscillating and did not restart until the crystal temperature had reached about 23°C at the 2,776.3-hr mark.

After the chamber pressure improved enough to start the second test series, the TQCM S/N 5 mass accumulation was much less. A TGA was then performed on the condensed material and is recorded in Fig. 23. The material starts to evaporate at about 290 K.

## **5.0 CONCLUDING REMARKS**

Based on results of the TQCM and FEB operational tests, the following points should be emphasized:

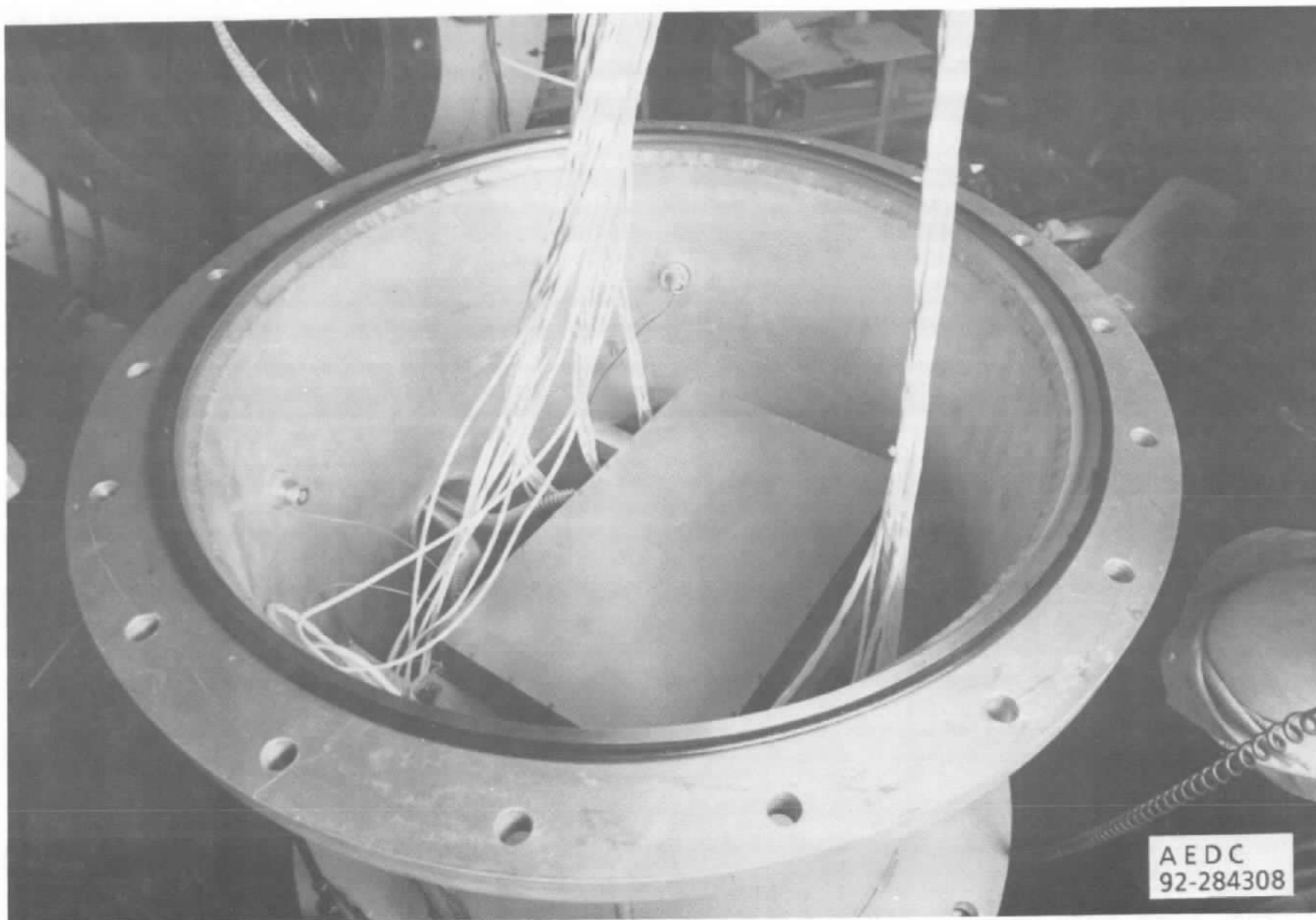
1. When power to the FEB was interrupted, operation of the QCMs resumed when power was restored. However, there were some large starting transients.
2. All the TQCMs exhibited a frequency increase when mass was deposited on them, indicating proper crystal orientation.
3. At the -195°C TQCM base temperature during the thermal vacuum test, only S/N 5's Peltier temperature control unit would operate. The Peltier units in TQCM S/Ns 2, 3, 5, and 6 all operated at the higher temperatures tested. However, Peltier units for S/Ns 2 and 6 failed in later tests and had to be repaired.
4. All of the TQCMs showed a frequency variation with crystal temperature and with mounting base temperature, with the crystal temperature effect being larger.
5. After crystal or TQCM mounting base temperature had been changed, it took a long time for the TQCM frequencies to settle out. Also, at the beginning of a crystal temperature change, frequency changes occurred before the crystal temperature readout had changed appreciably.
6. The FEB mounting base temperature did not have a large effect on frequency.
7. During the first, or 21-day drift test, the TQCMs' frequencies changed less than 0.5 Hz/day, except for S/N 3. S/N 3 changed about 1.6 Hz/day, but that was attributed to a mass pickup. During the second, or 28-day drift test, S/N 3 frequency changed less than 0.5 Hz/day.

8. There were two instances when the chamber pressure indicated that there was large outgassing when the chamber was being pumped down. Both of these instances occurred when the FEB and flight cable were installed in the chamber after having been out. In the first instance (the initial installation), a vacuum bake-out of the flight cable relieved much of the outgassing. In the second instance (after removal for testing at Utah State University), 2 days of continuous vacuum pumping with a turbomolecular pump and a cryopump removed most of the outgassing.

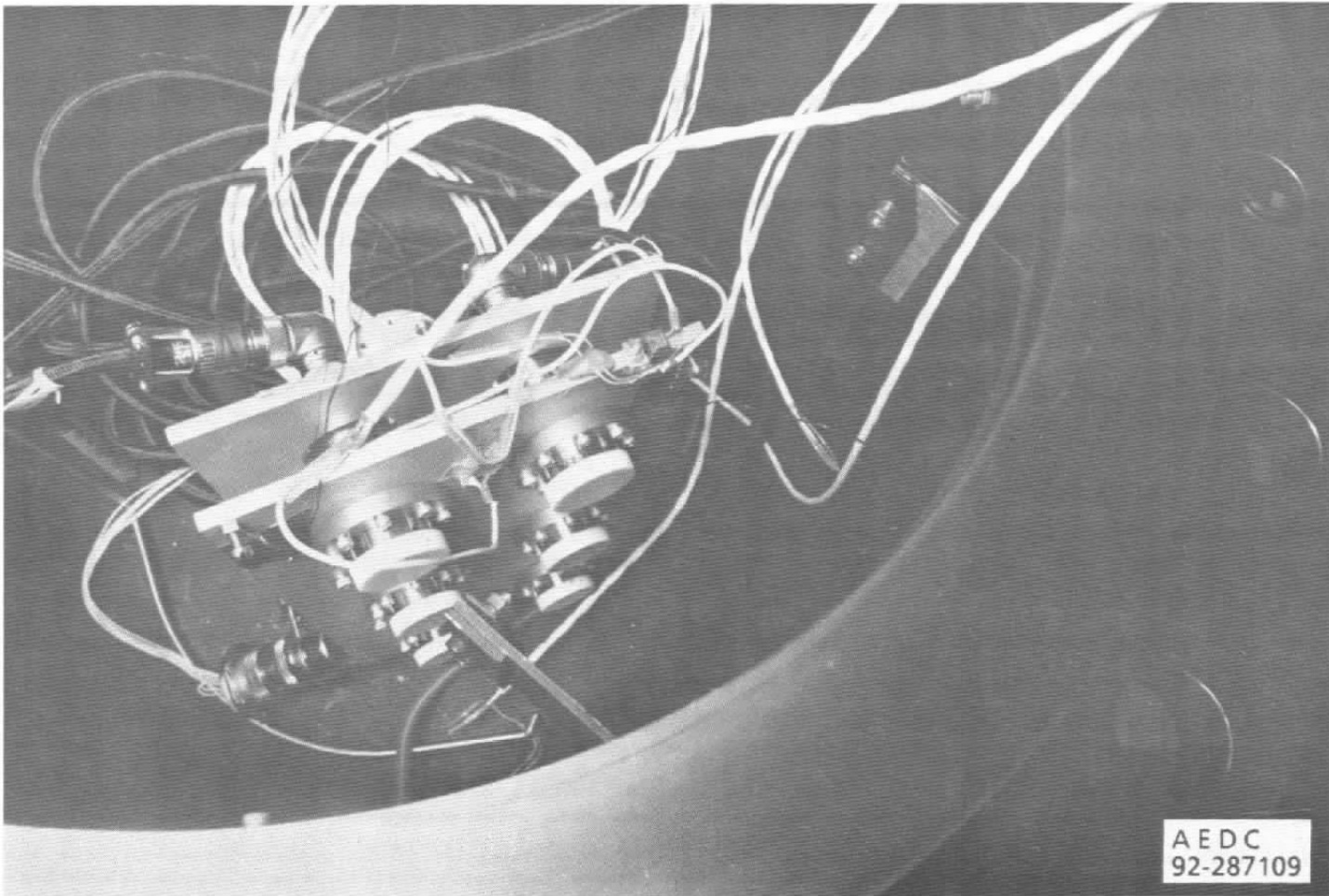


a. Test chamber

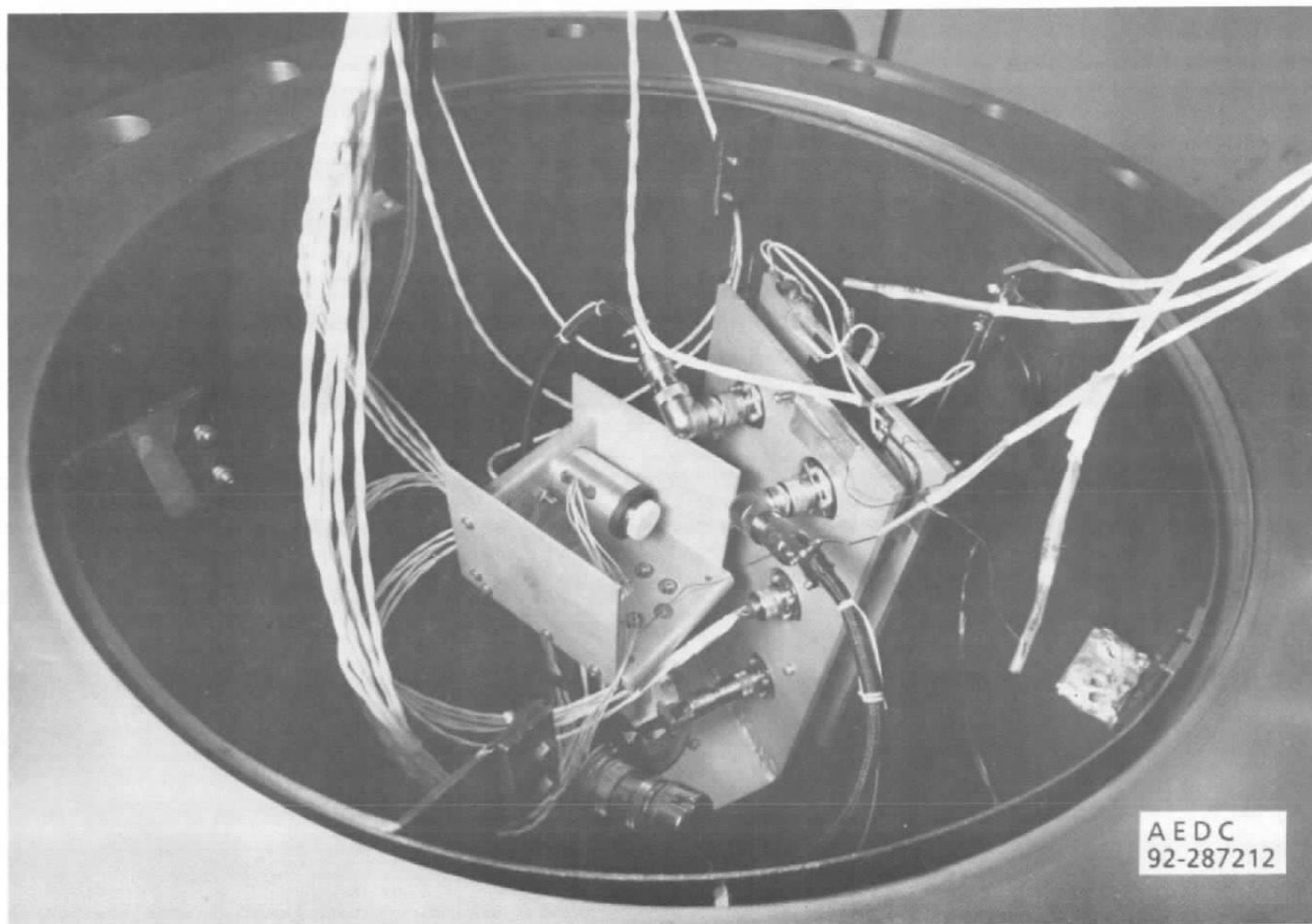
Figure 1. Photographs of test chamber.



**b. FEB mounted to base in upper chamber**  
**Figure 1. Continued.**



c. TQCMs mounted to base in cryopump  
Figure 1. Continued.



d. CQCM mounted to second stage of cryopump  
Figure 1. Concluded.

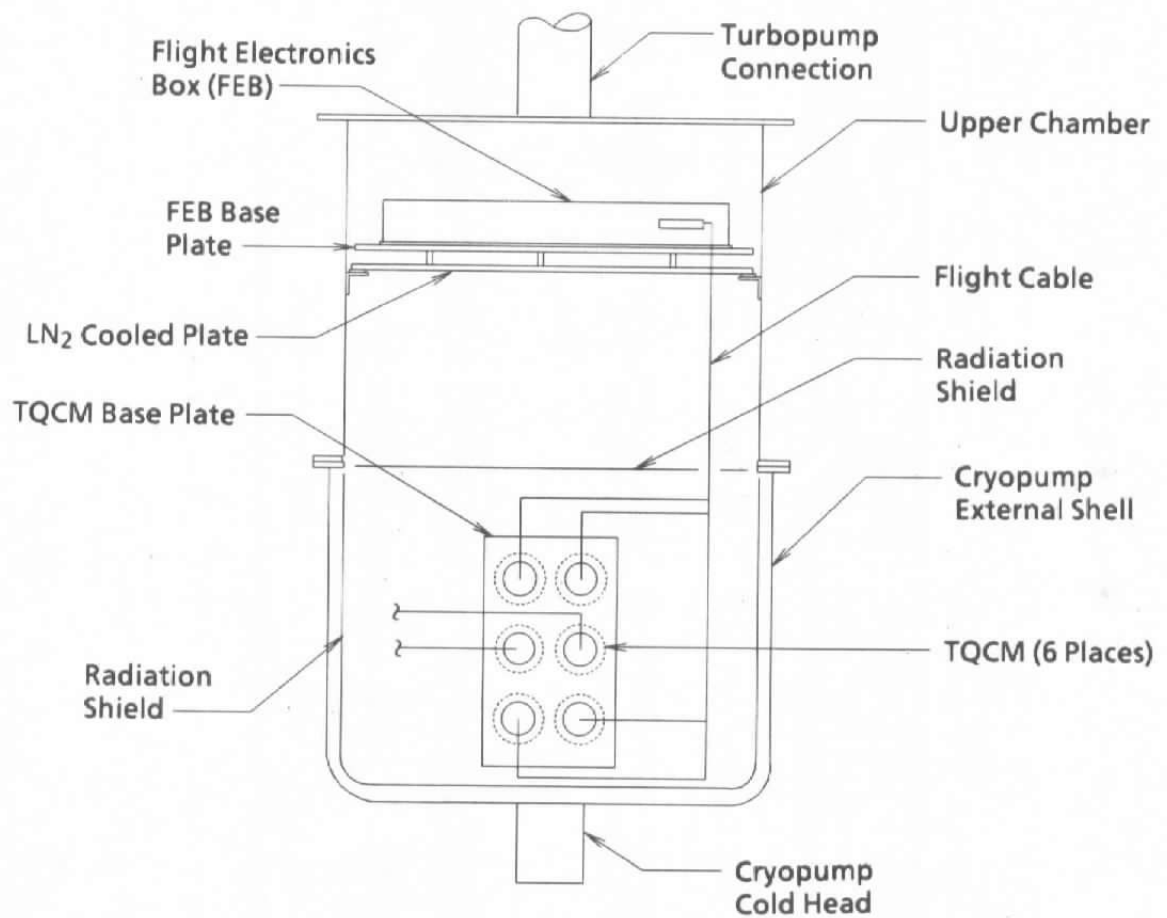


Figure 2. Location of TQCMs and FEB in test chamber.

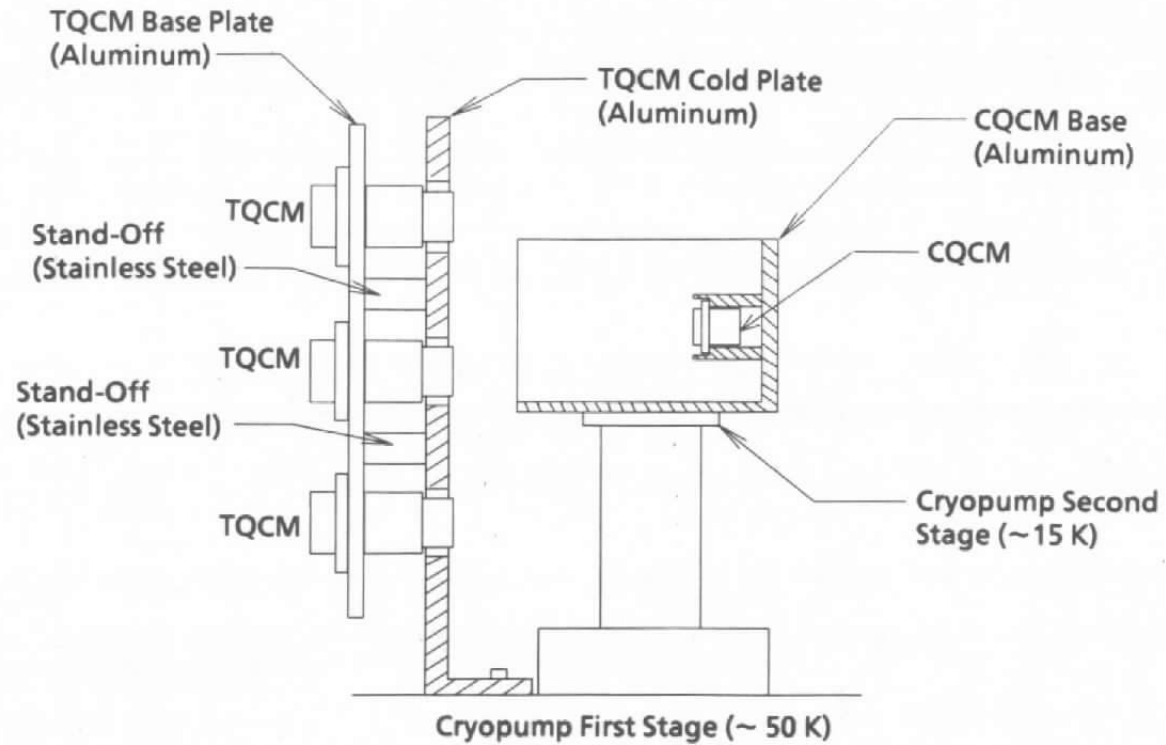


Figure 3. Cooling sources for TQCM and FEB bases.

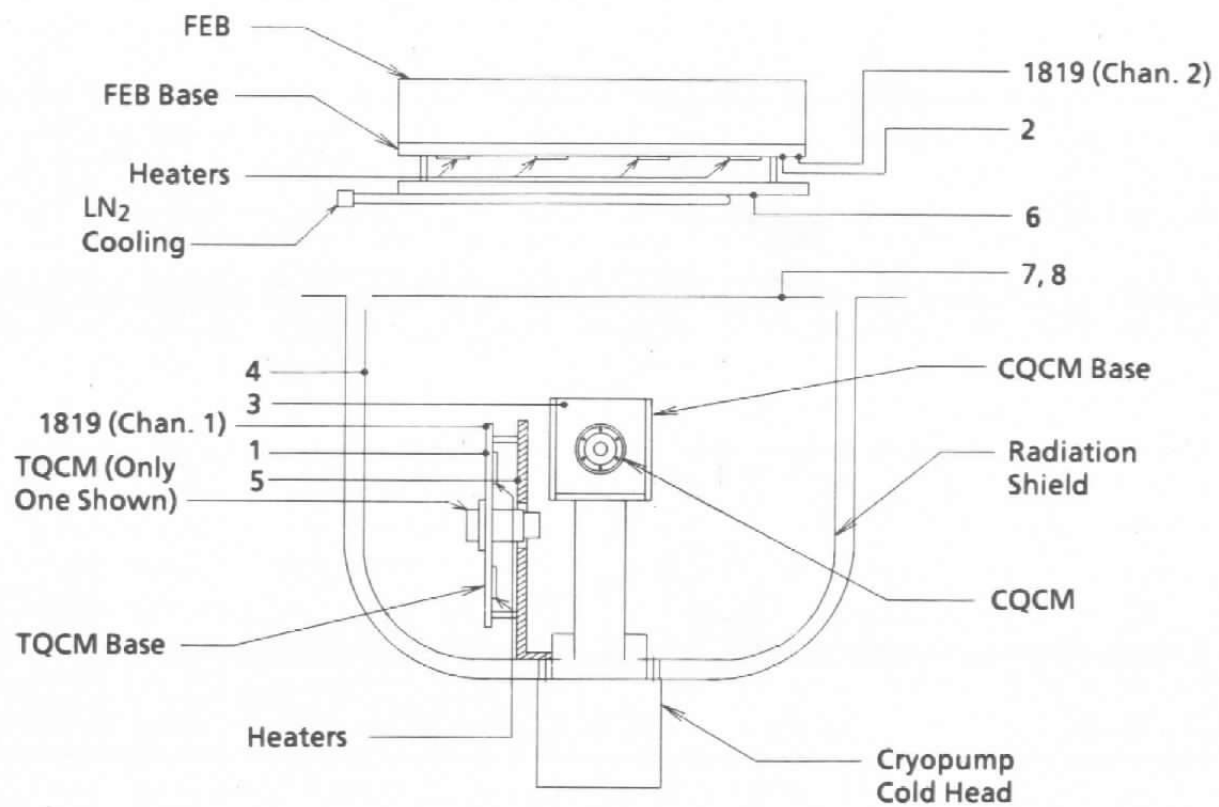


Figure 4. Location of silicon diode temperature sensors.

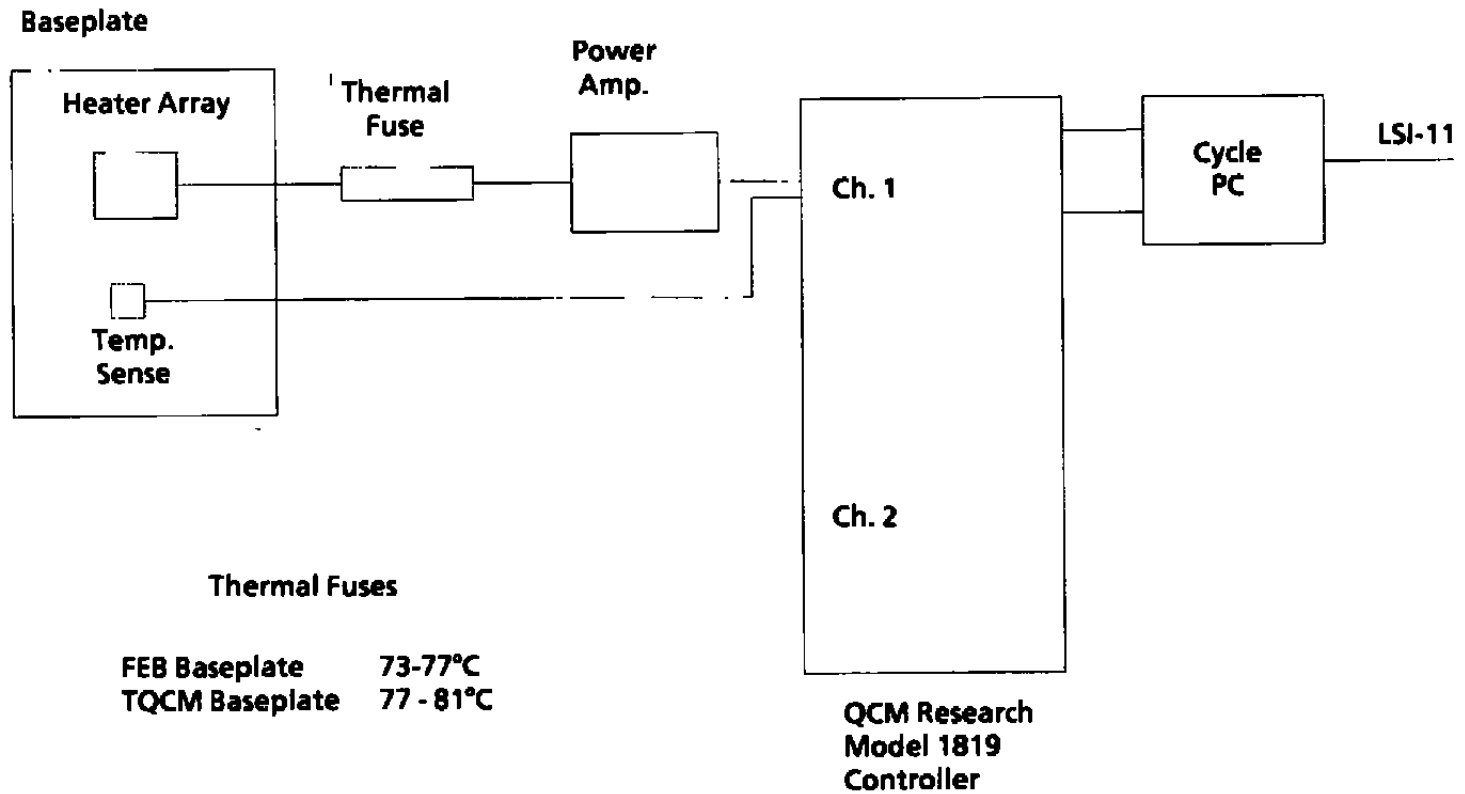


Figure 5. Plate heater system.

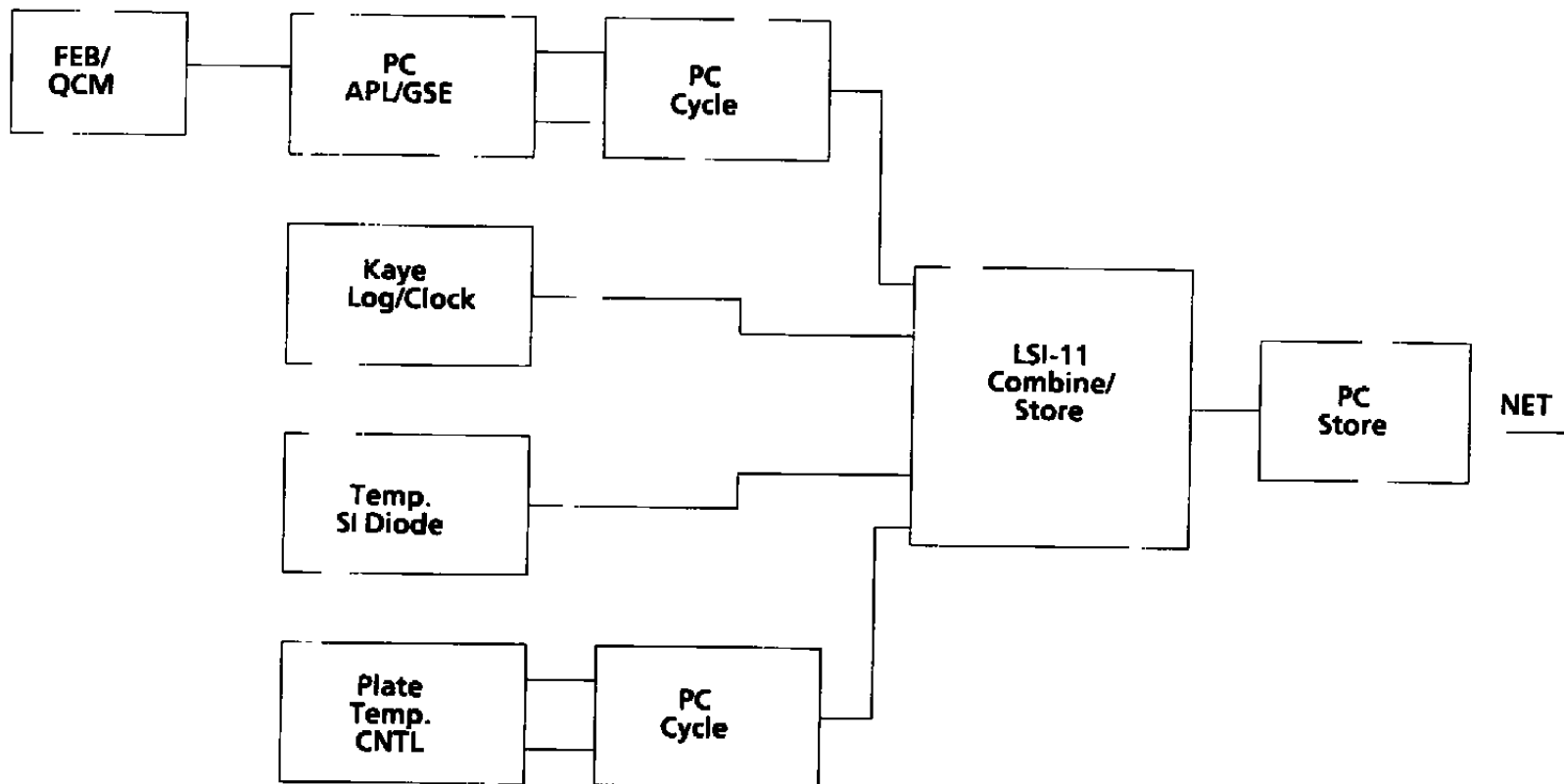


Figure 6. Block diagram of systems for TQCM test.

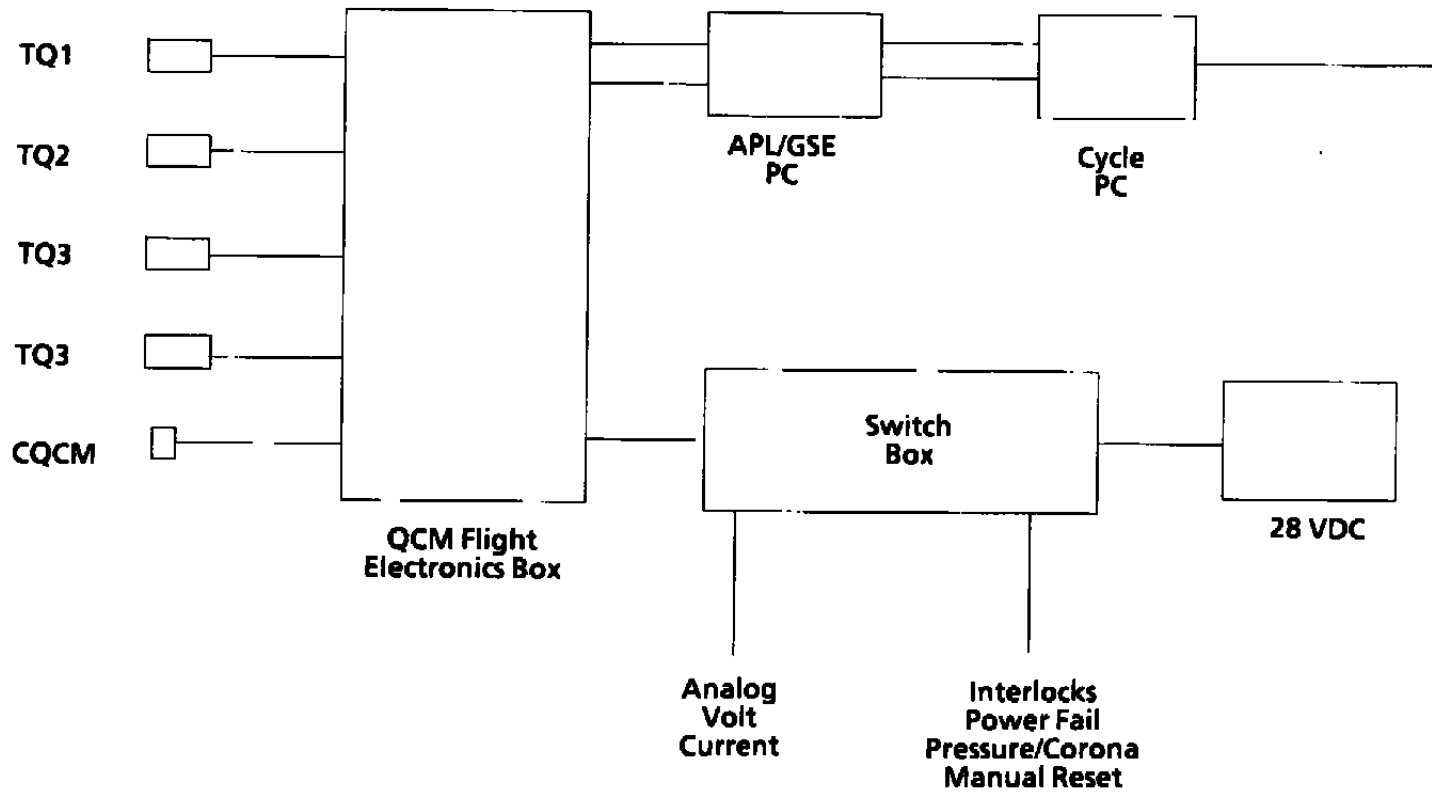


Figure 7. QCM flight electronics system.

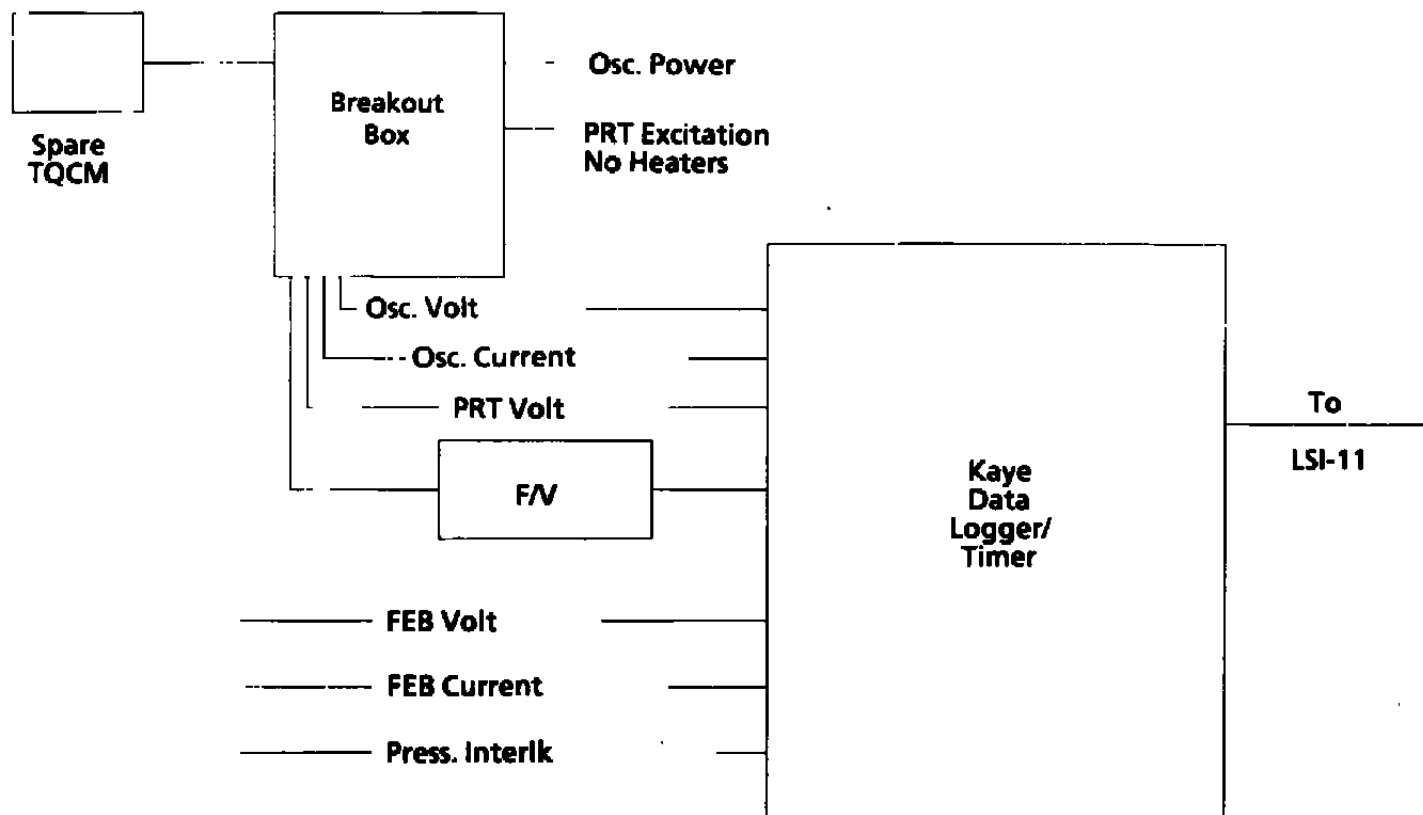


Figure 8. Data logger system.

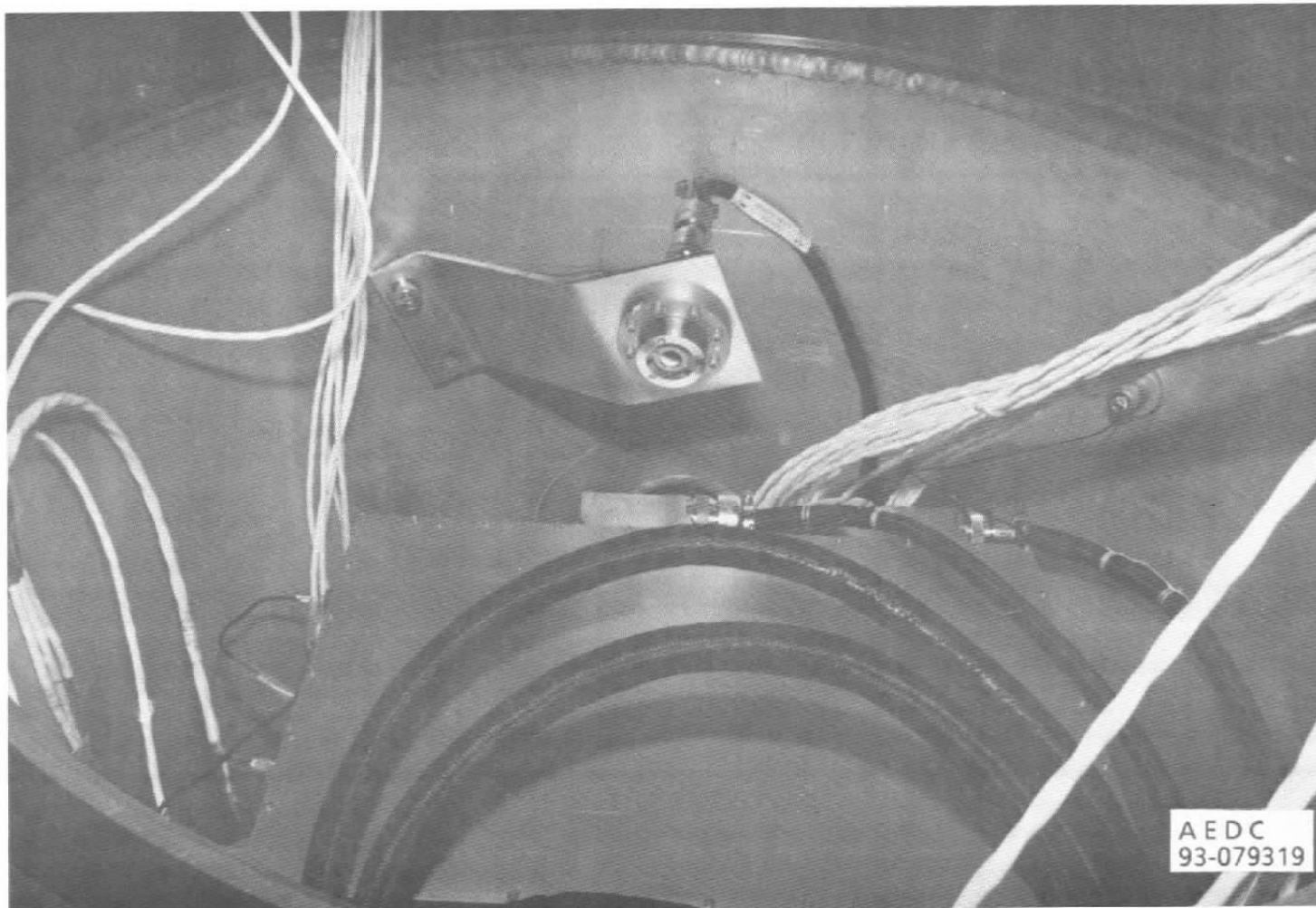
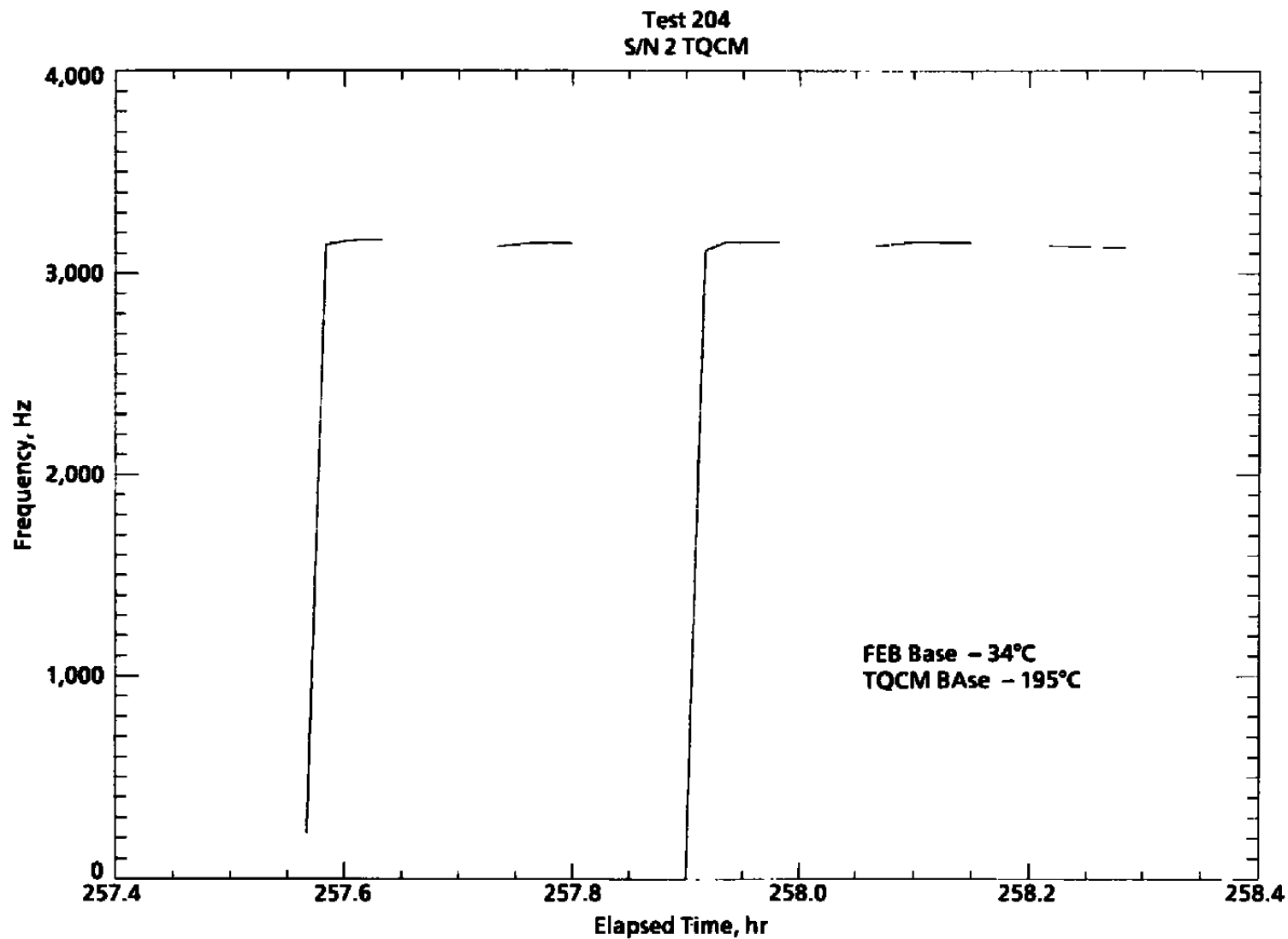
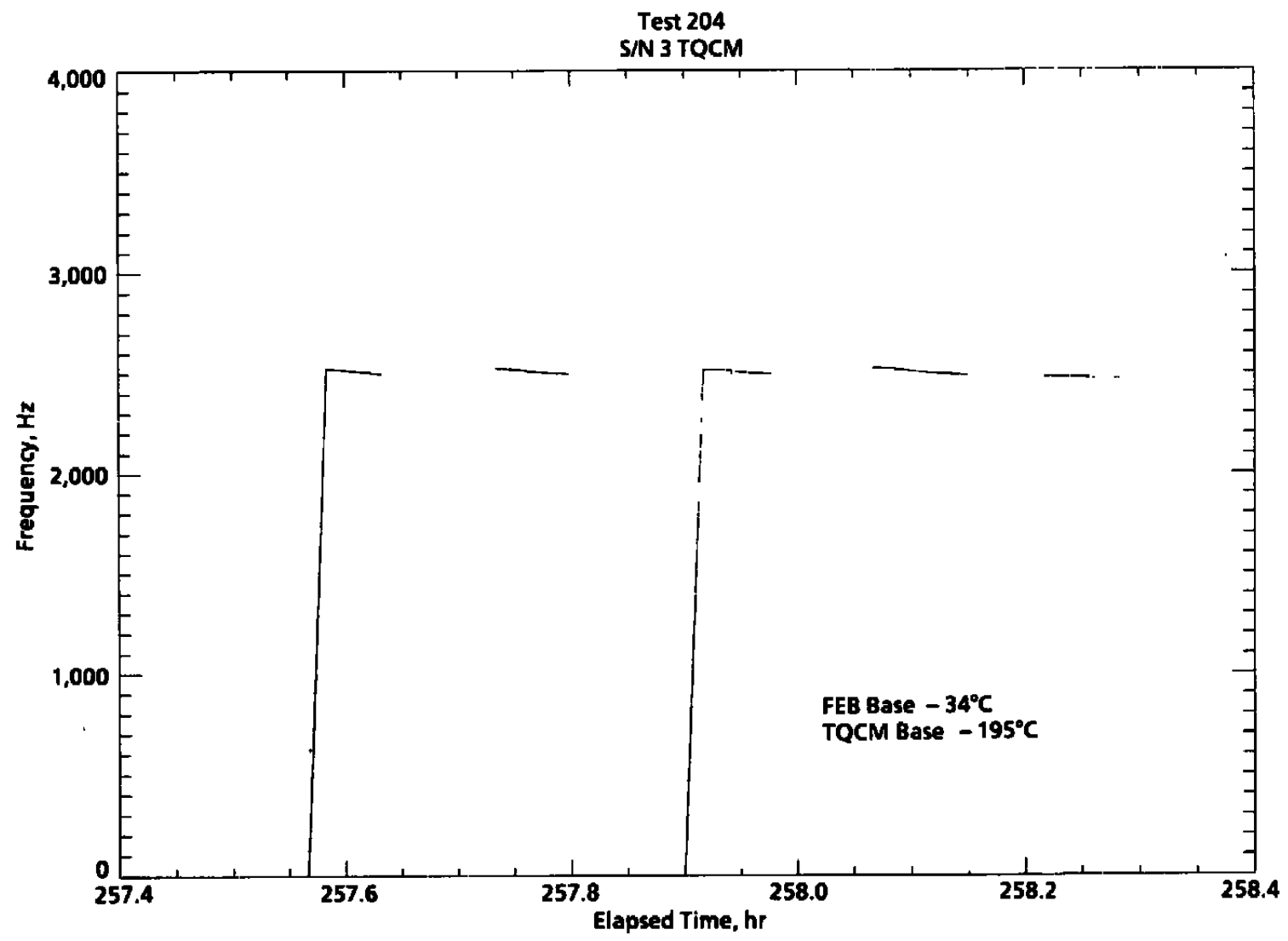


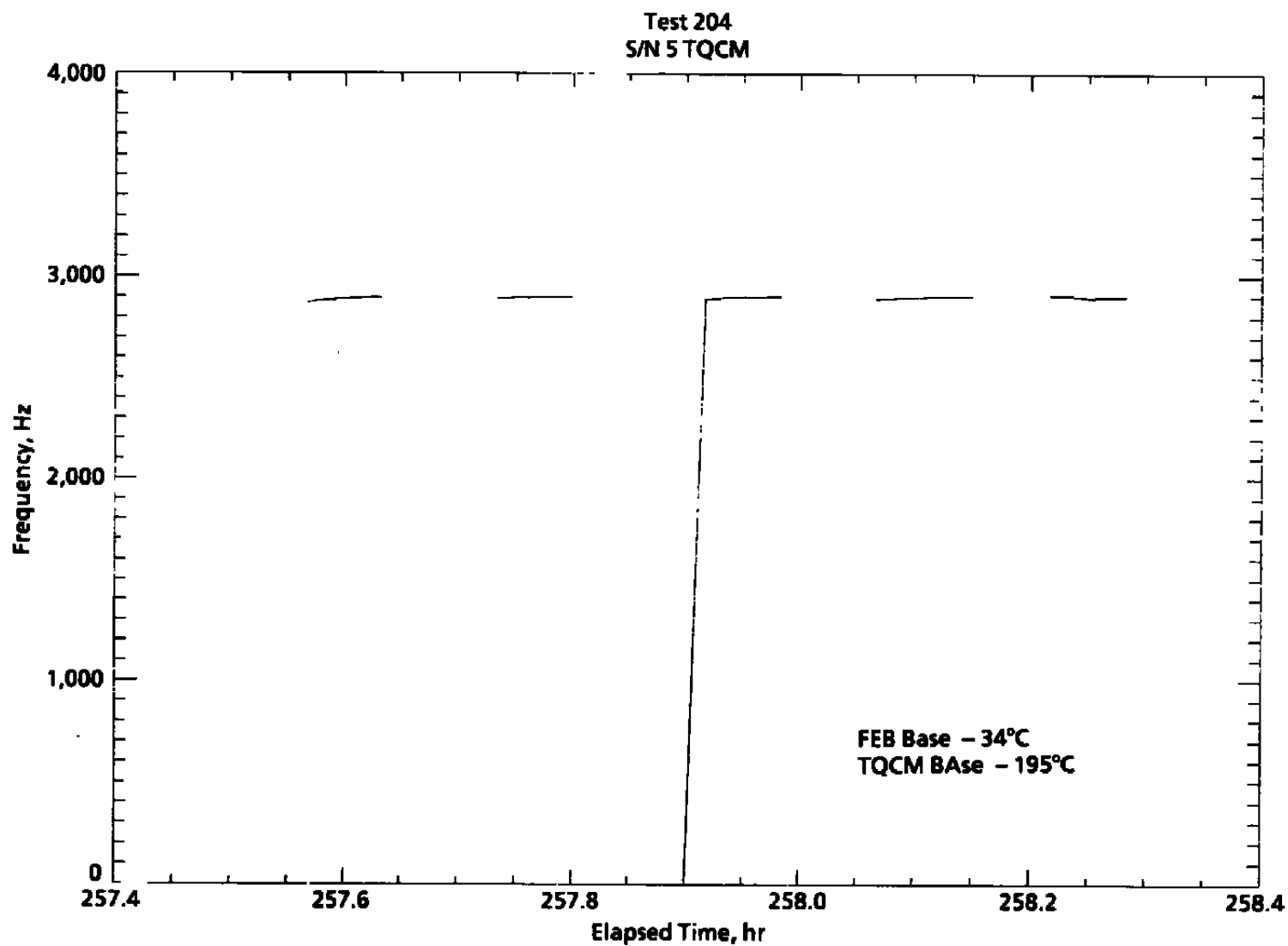
Figure 9. TQCM S/N 5 mounted in upper chamber.



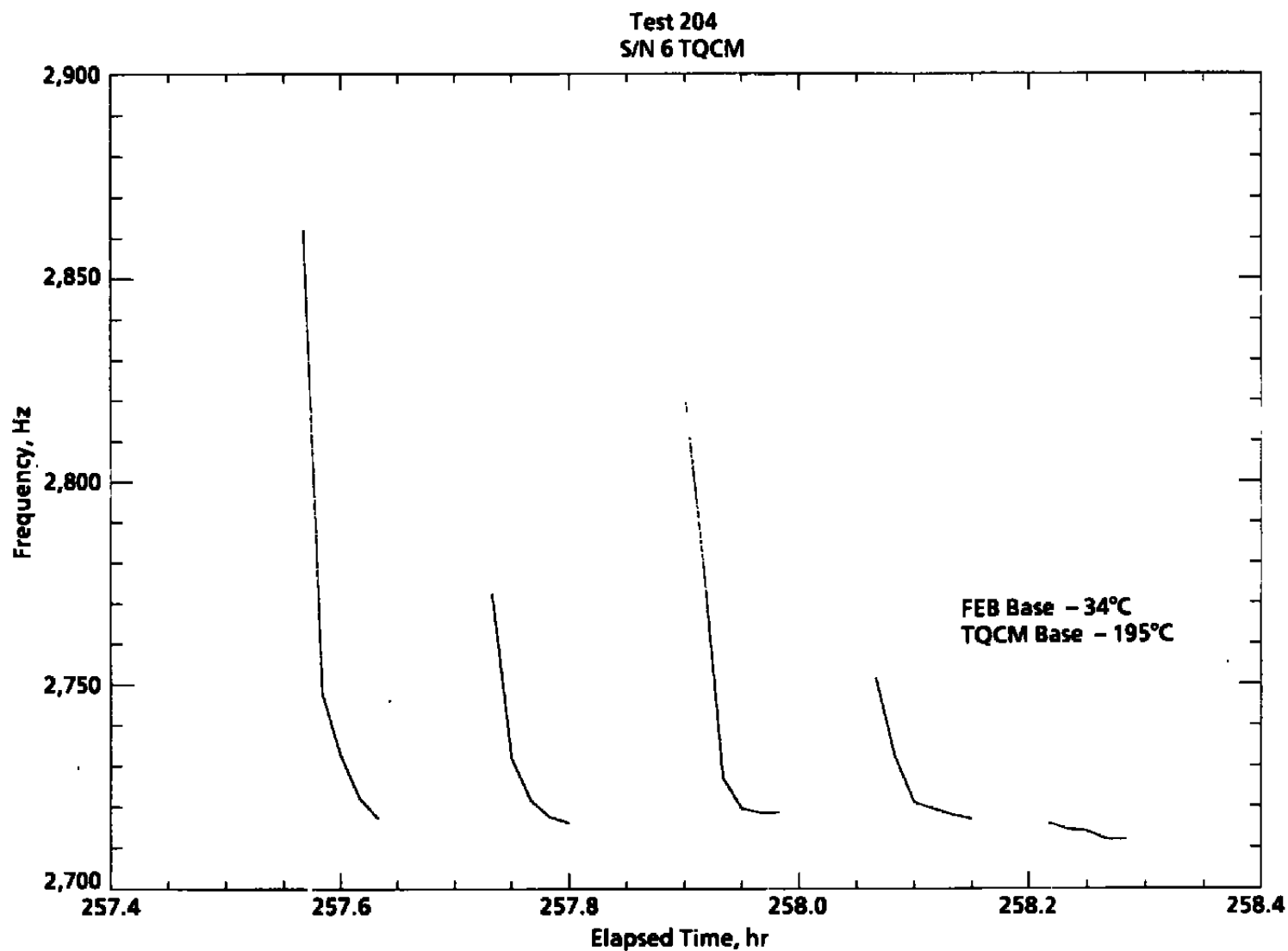
a. TQCM S/N 2  
Figure 10. FEB power on-off tests at -195°C.



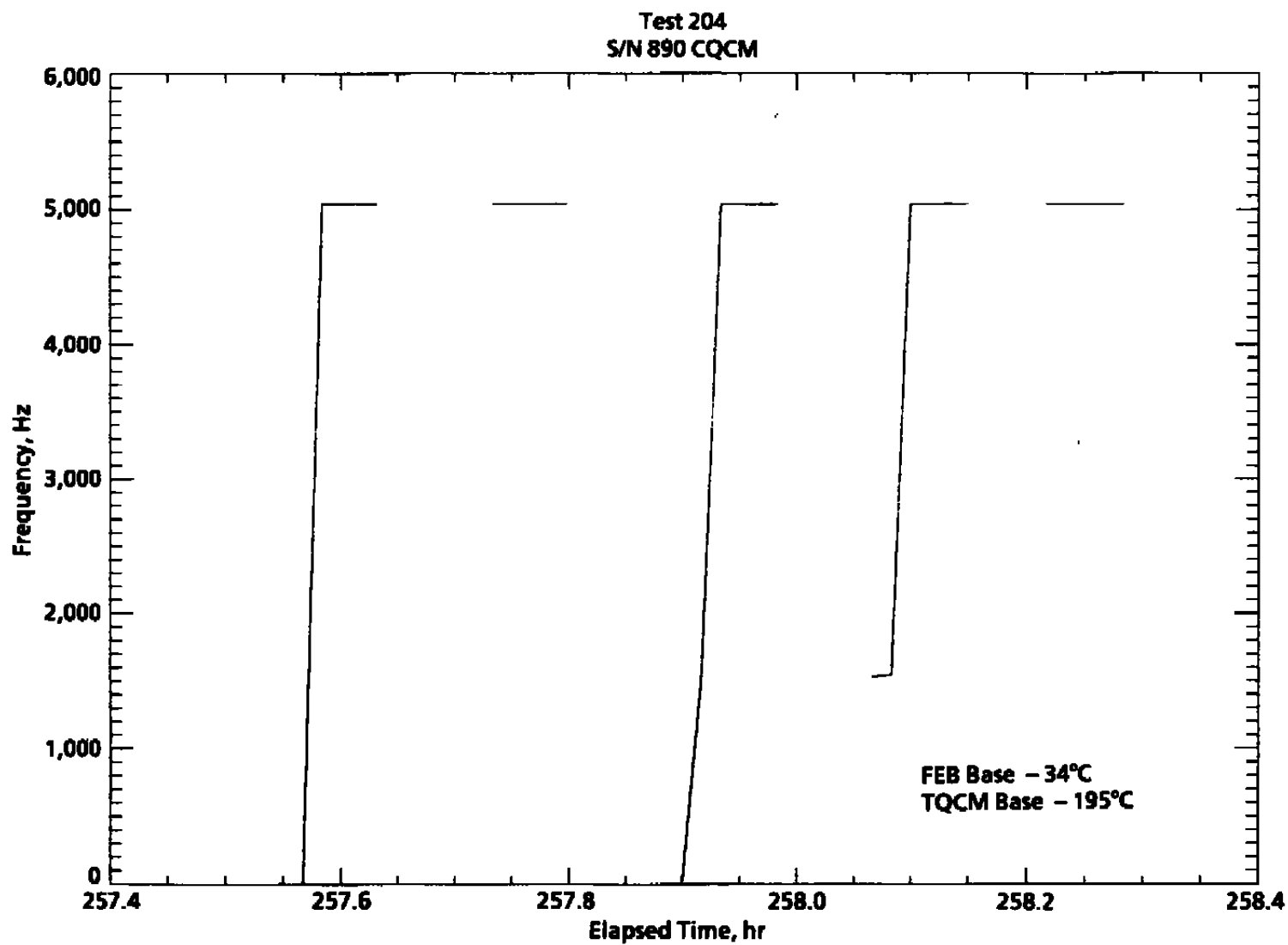
b. TQCM S/N 3  
Figure 10. Continued.



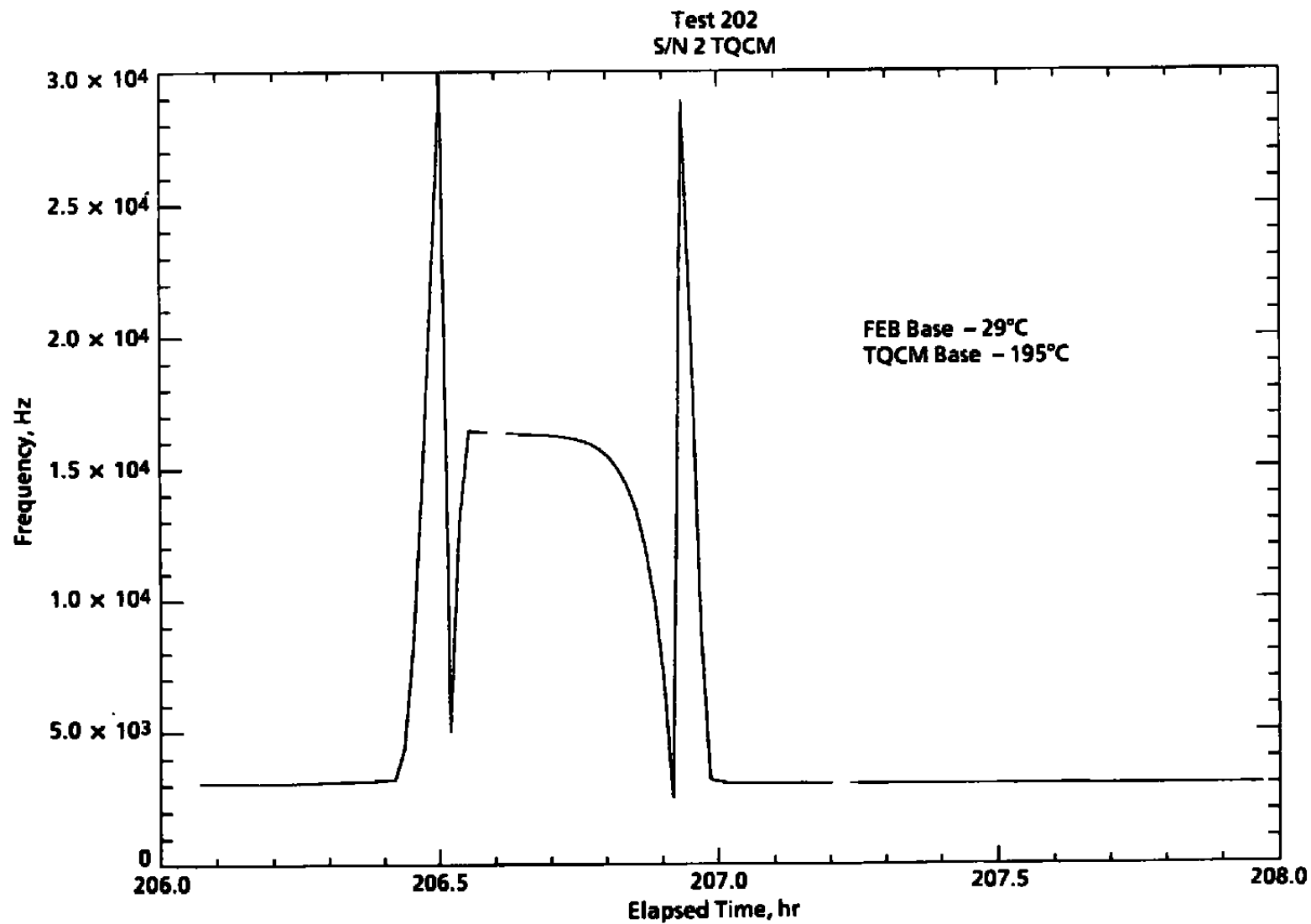
c. TQCM S/N 5  
Figure 10. Continued.



**d. TQCM S/N 6  
Figure 10. Continued.**



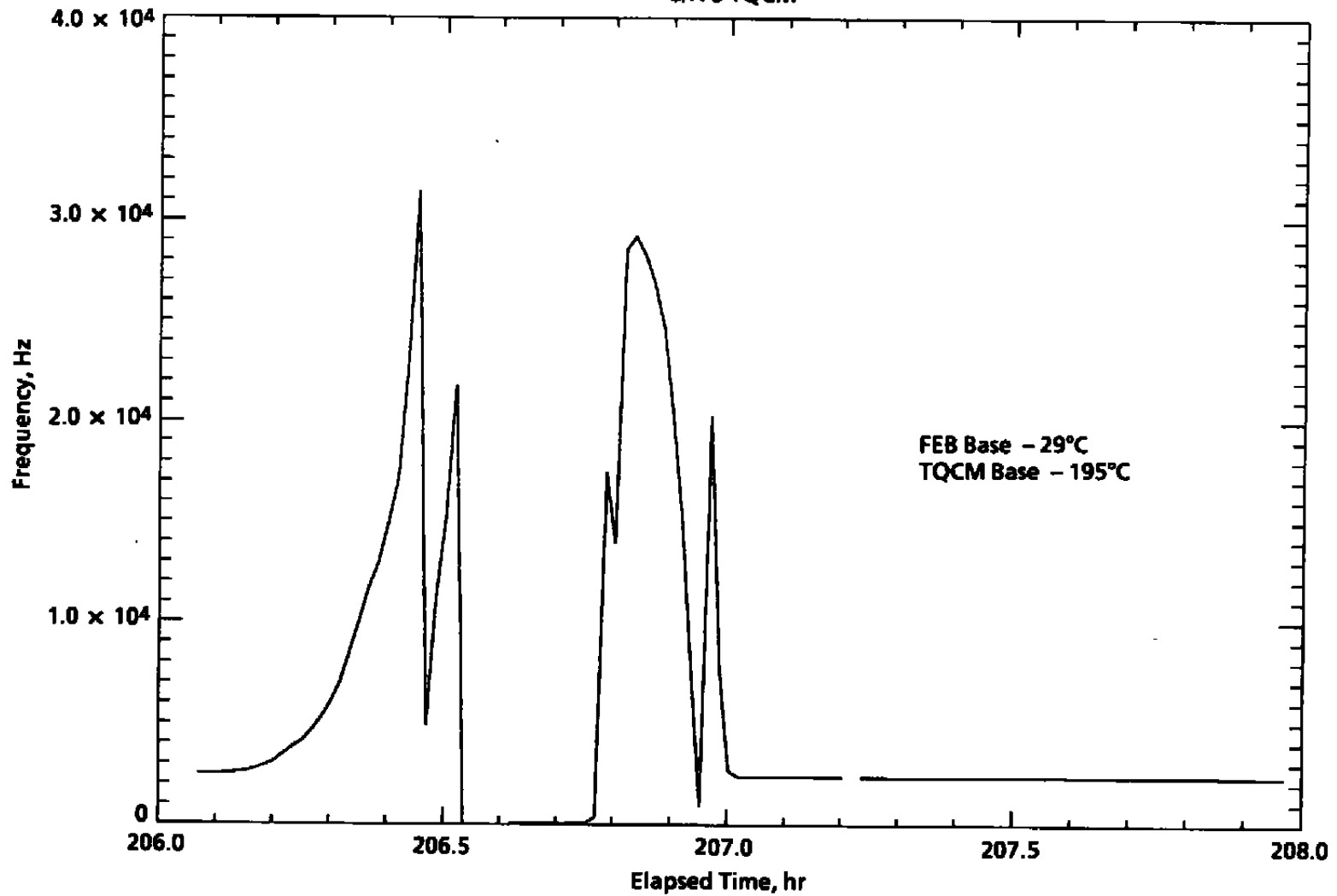
e. CQCM S/N 890  
Figure 10. Concluded.



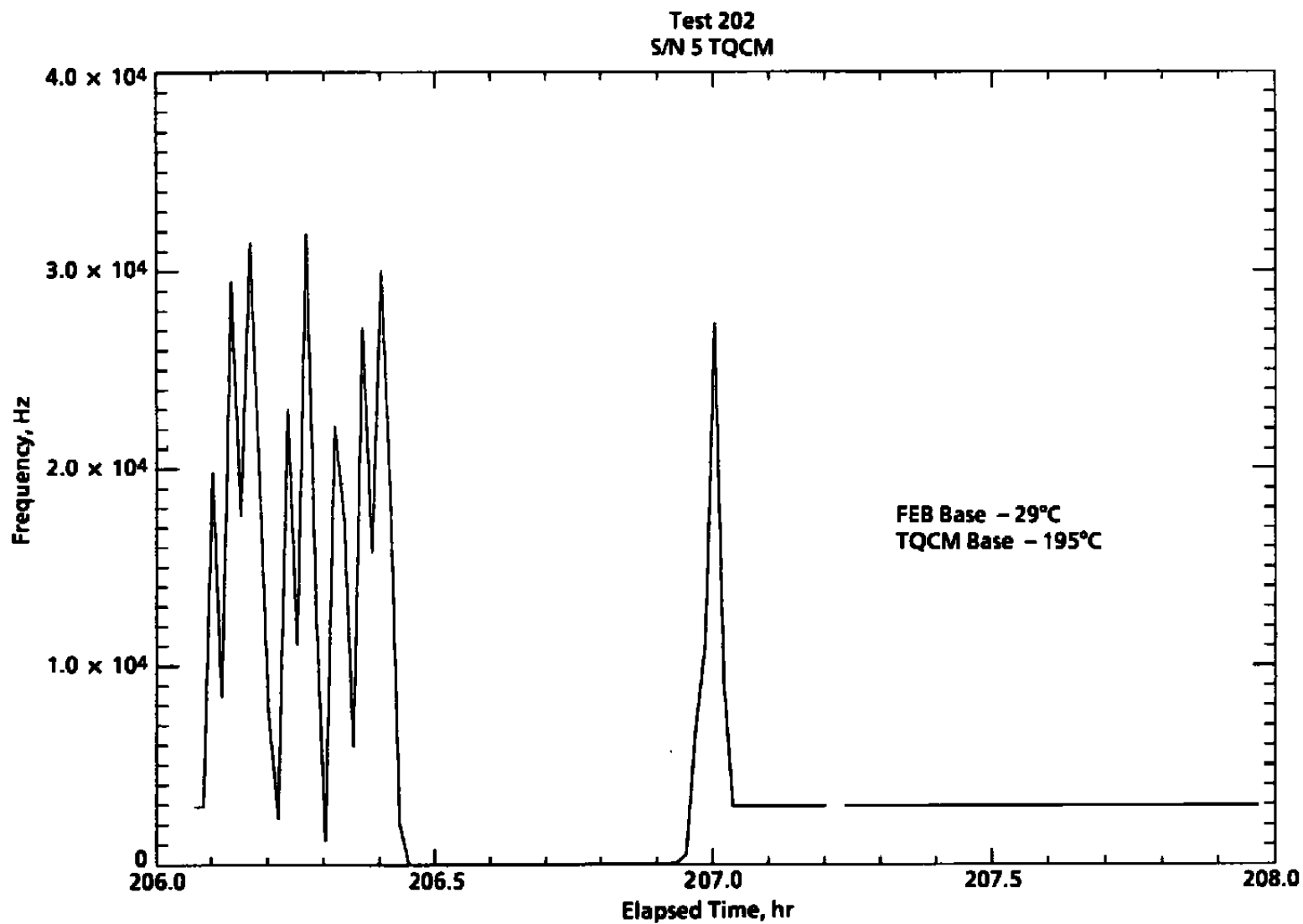
a. TQCM S/N 2

Figure 11. CO<sub>2</sub> condensation on TQCMs.

Test 202  
S/N 3 TQCM

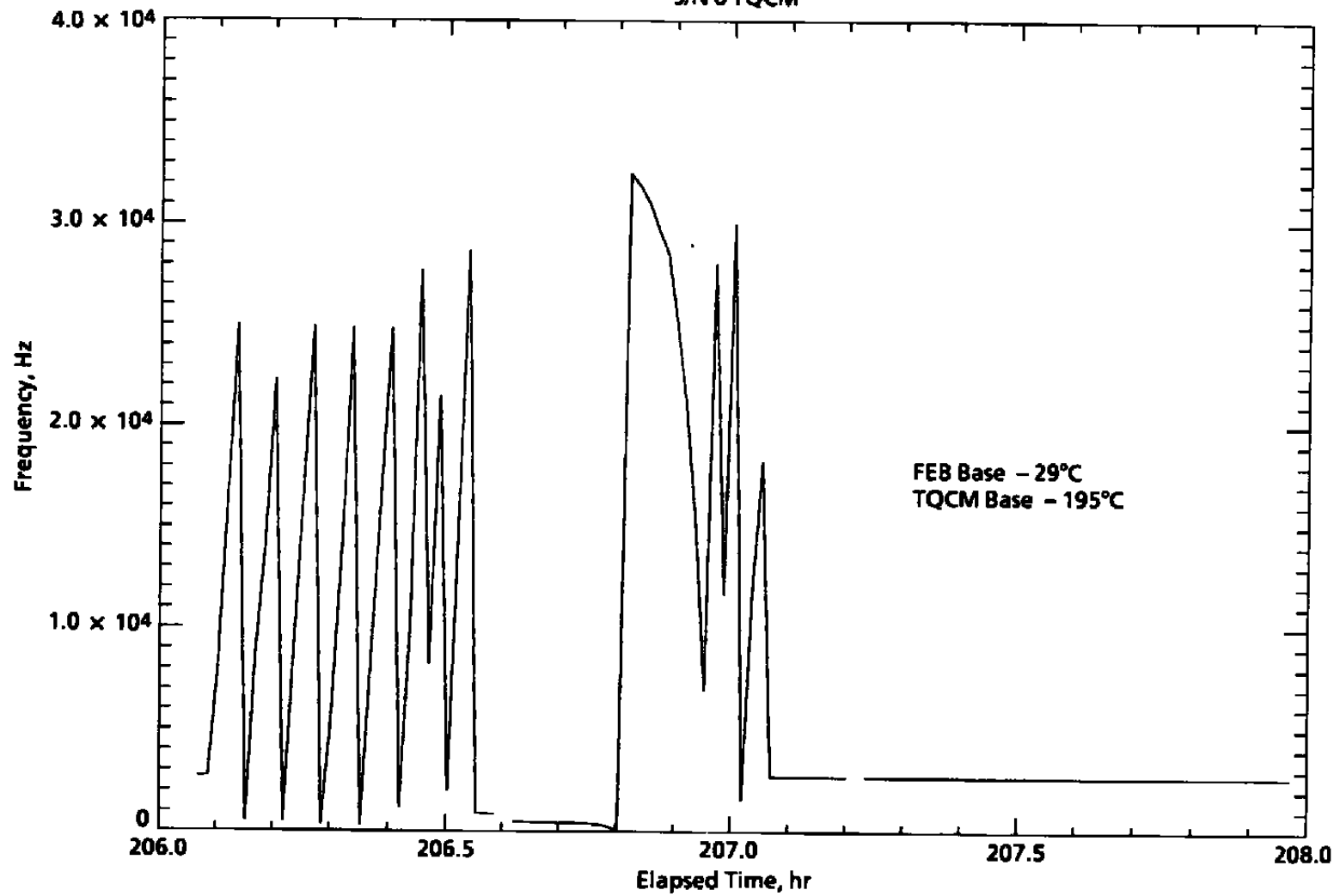


b. TQCM S/N 3  
Figure 11. Continued.

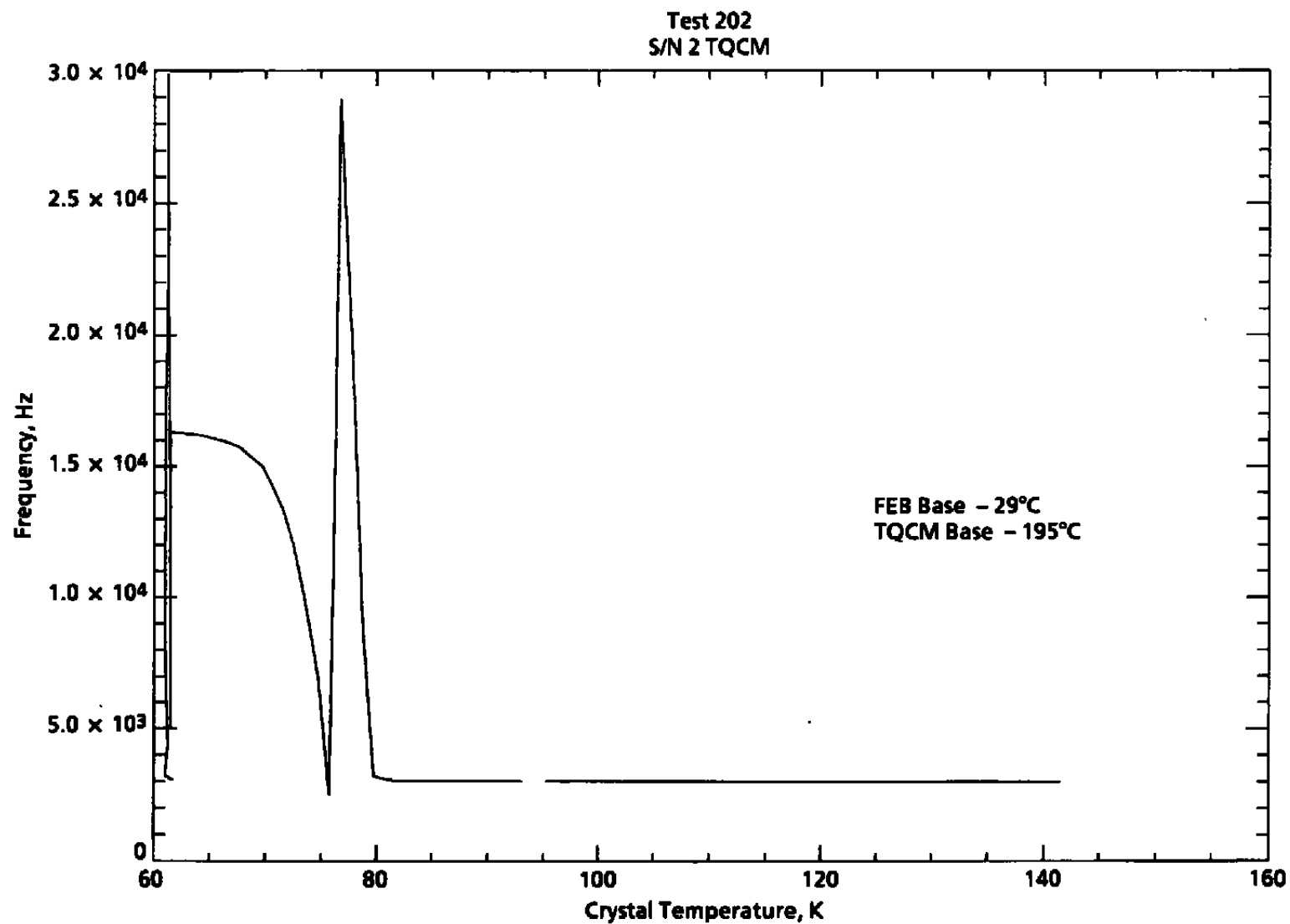


c. TQCM S/N 5  
Figure 11. Continued.

Test 202  
S/N 6 TQCM



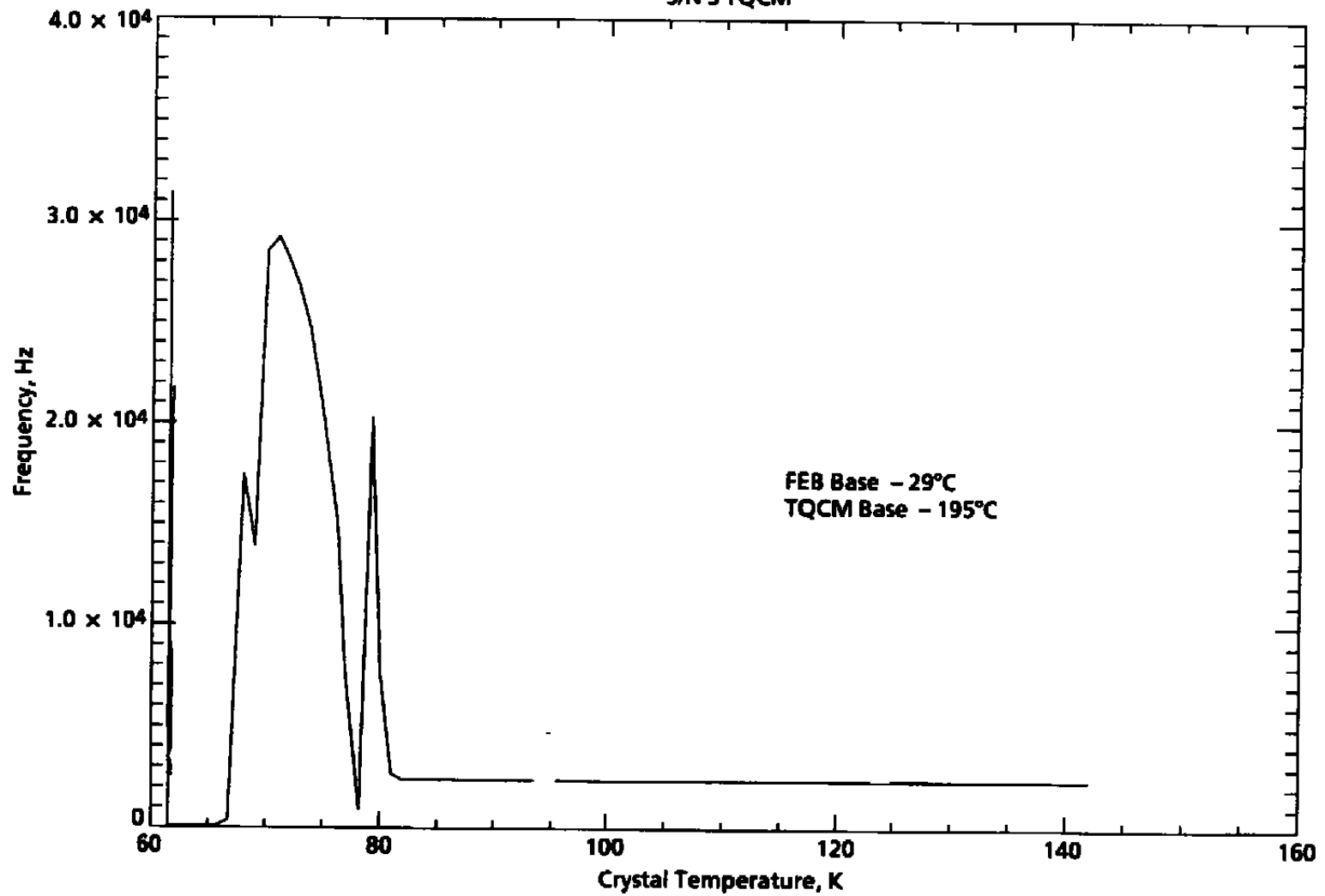
d. TQCM S/N 6  
Figure 11. Concluded.



a. TQCM S/N 2

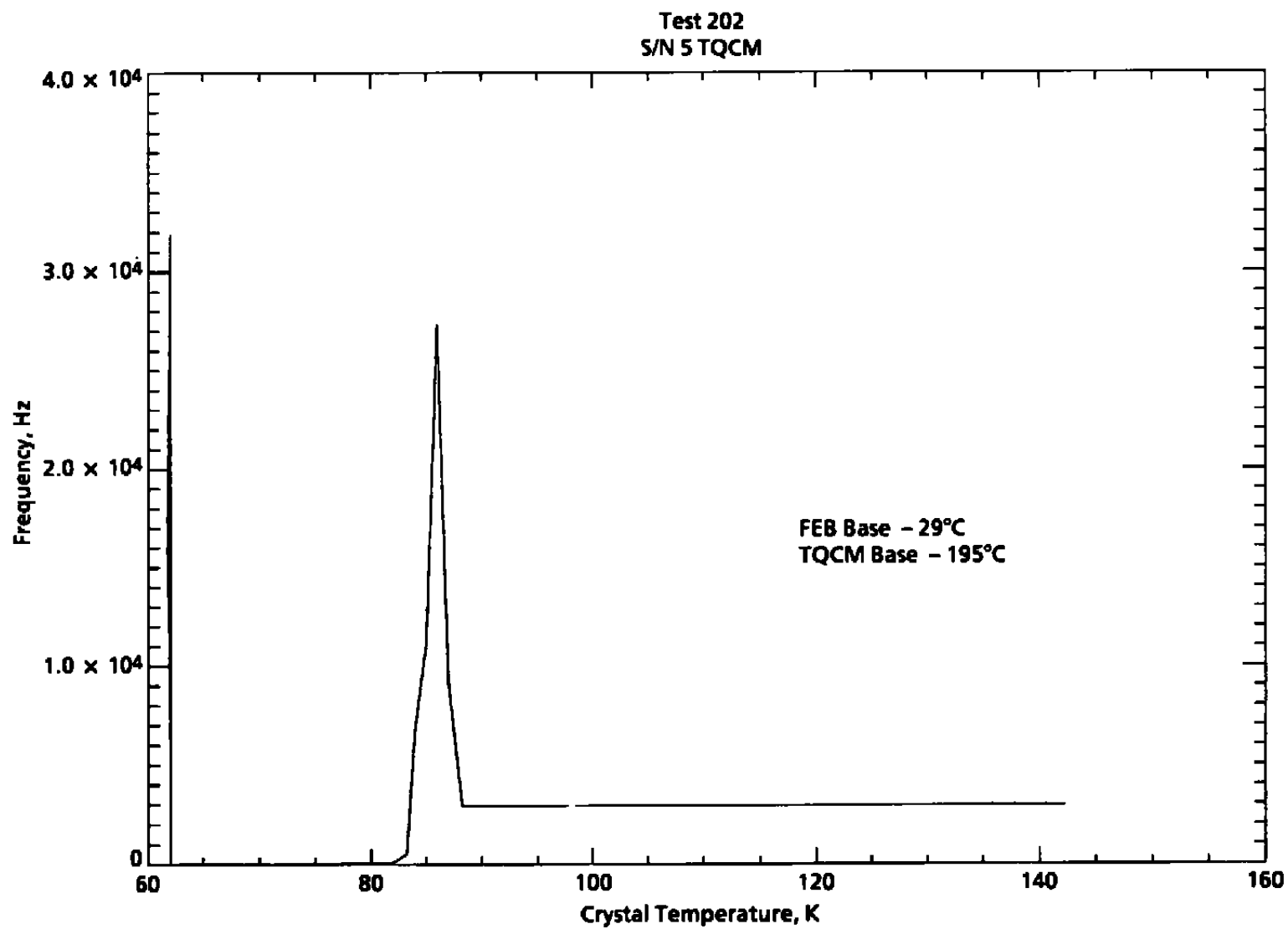
Figure 12. TGA of CO<sub>2</sub> on TQCMs.

Test 202  
S/N 3 TQCM



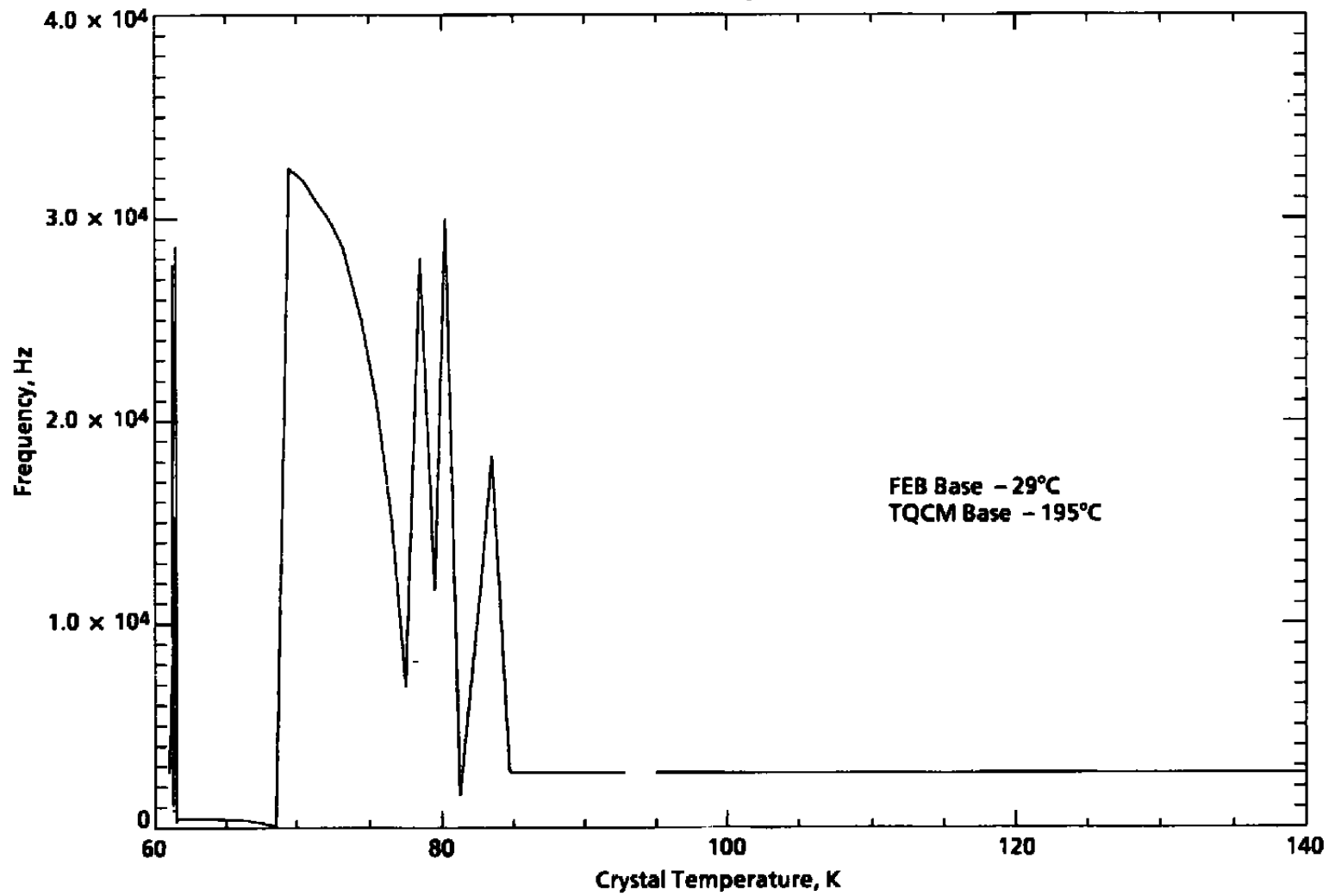
FEB Base - 29°C  
TQCM Base - 195°C

b. TQCM S/N 3  
Figure 12. Continued.

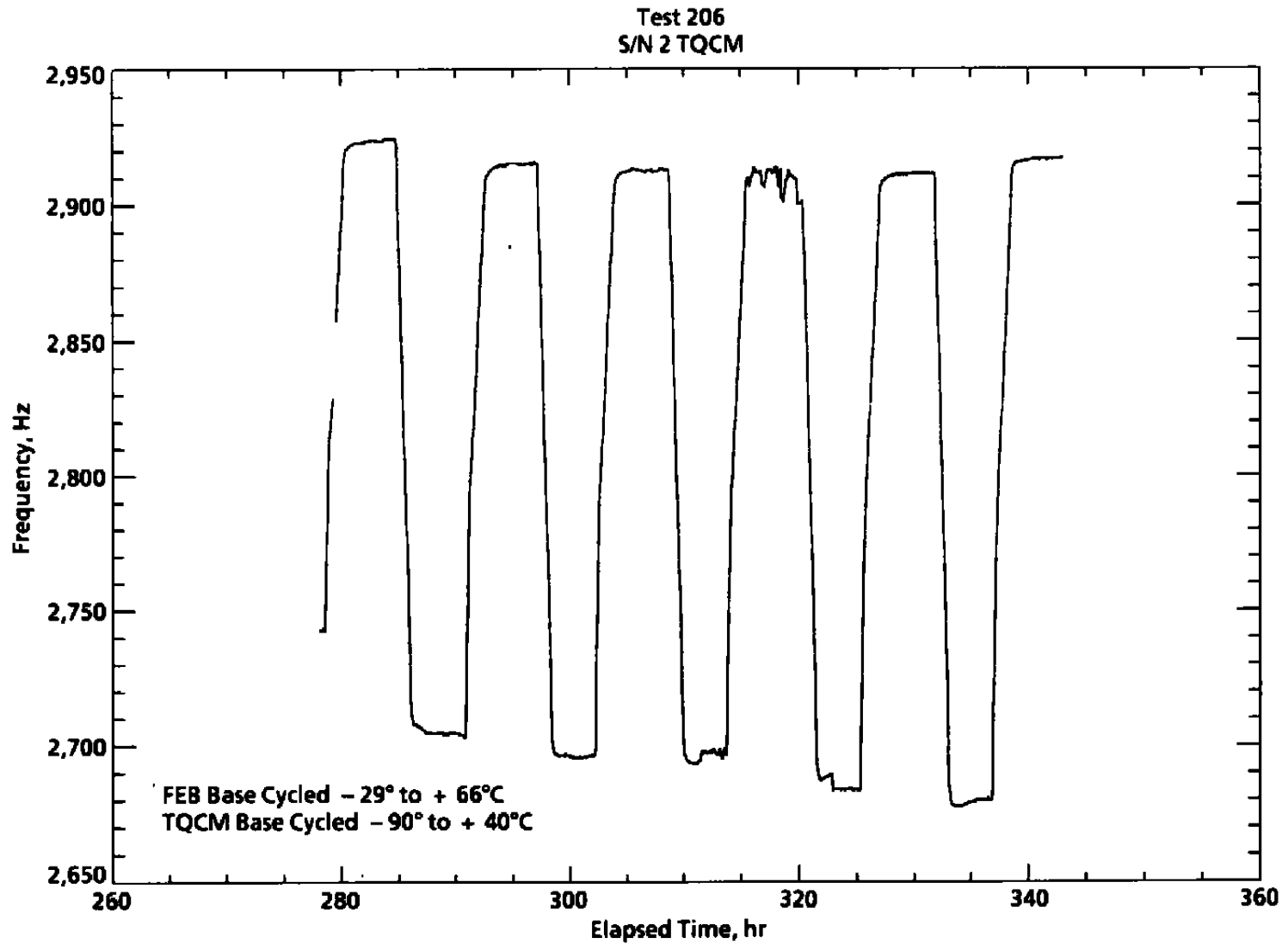


c. TQCM S/N 5  
Figure 12. Continued.

Test 202  
S/N 6 TQCM

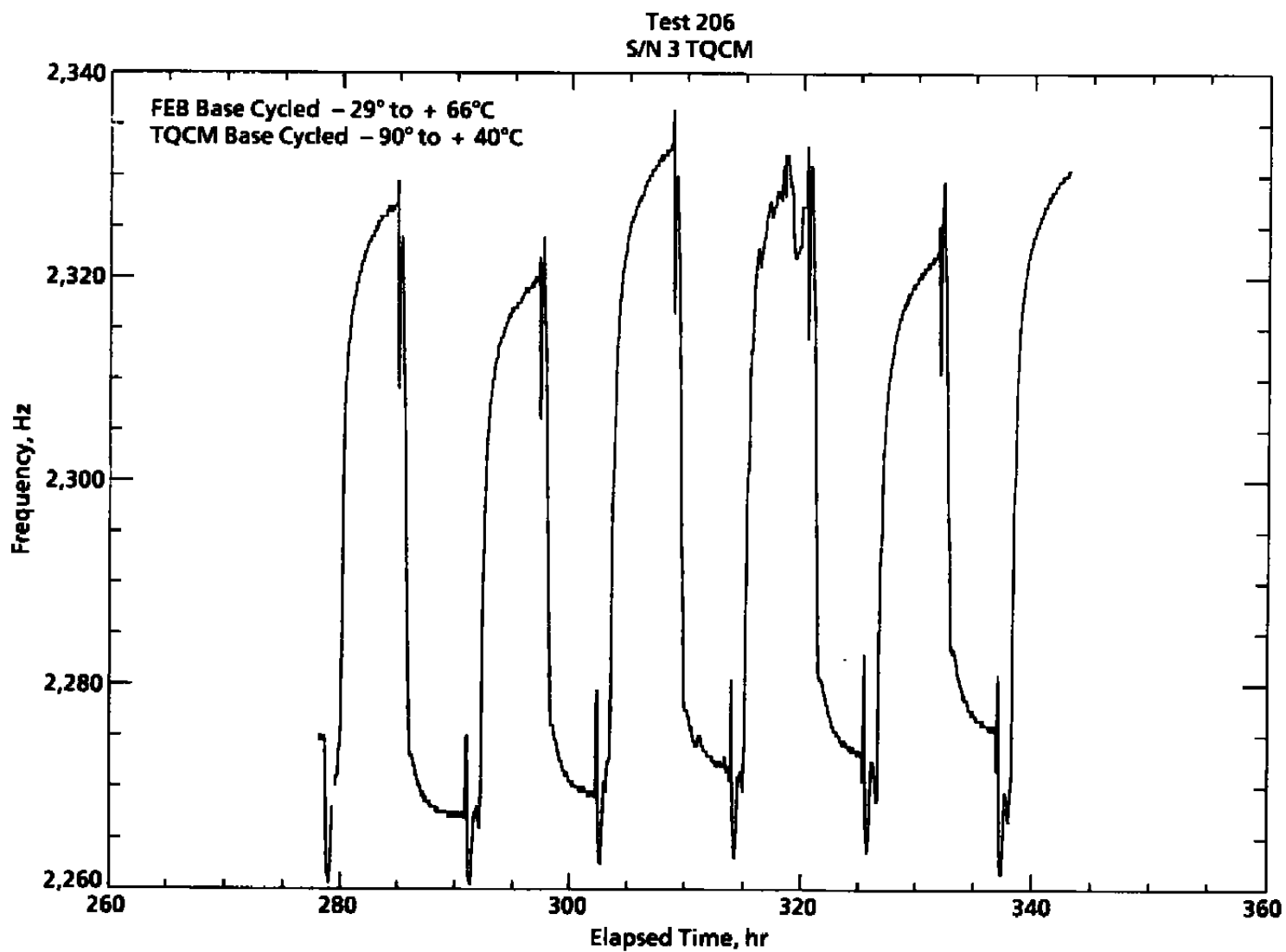


d. TQCM S/N 6  
Figure 12. Concluded.

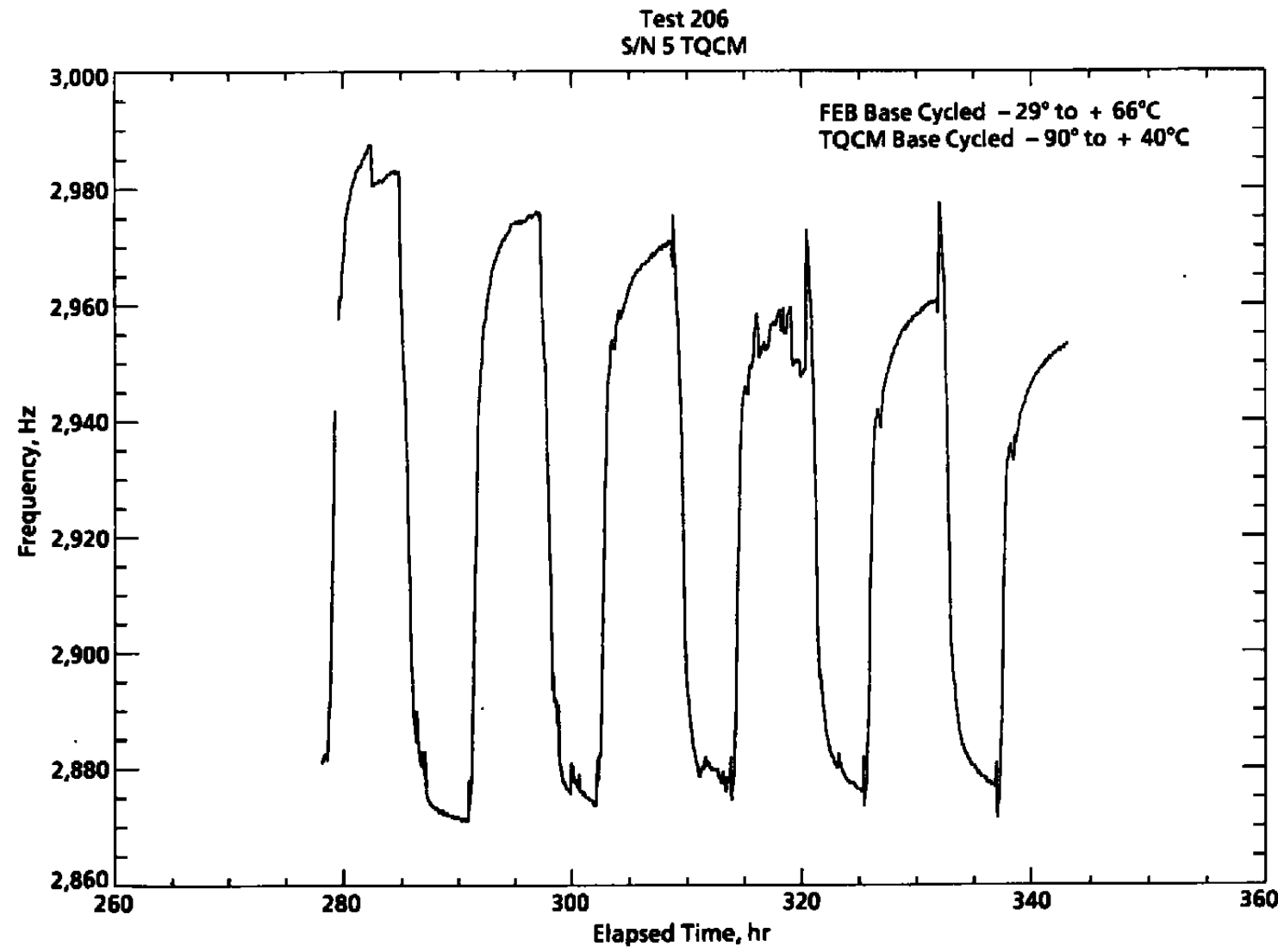


a. TQCM S/N 2

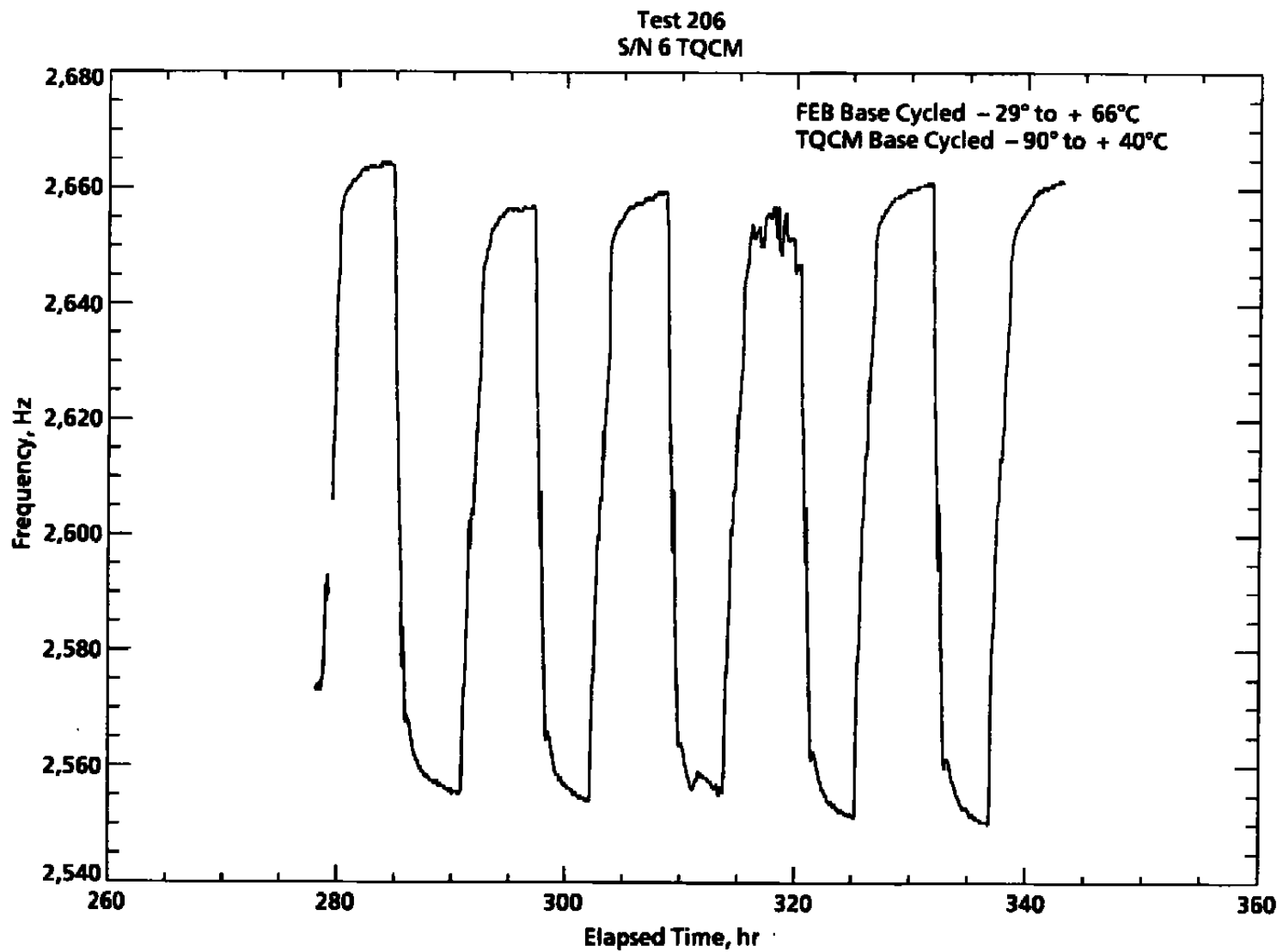
Figure 13. Frequency of QCMs while cycling temperatures of TQCM and FEB mounting bases.



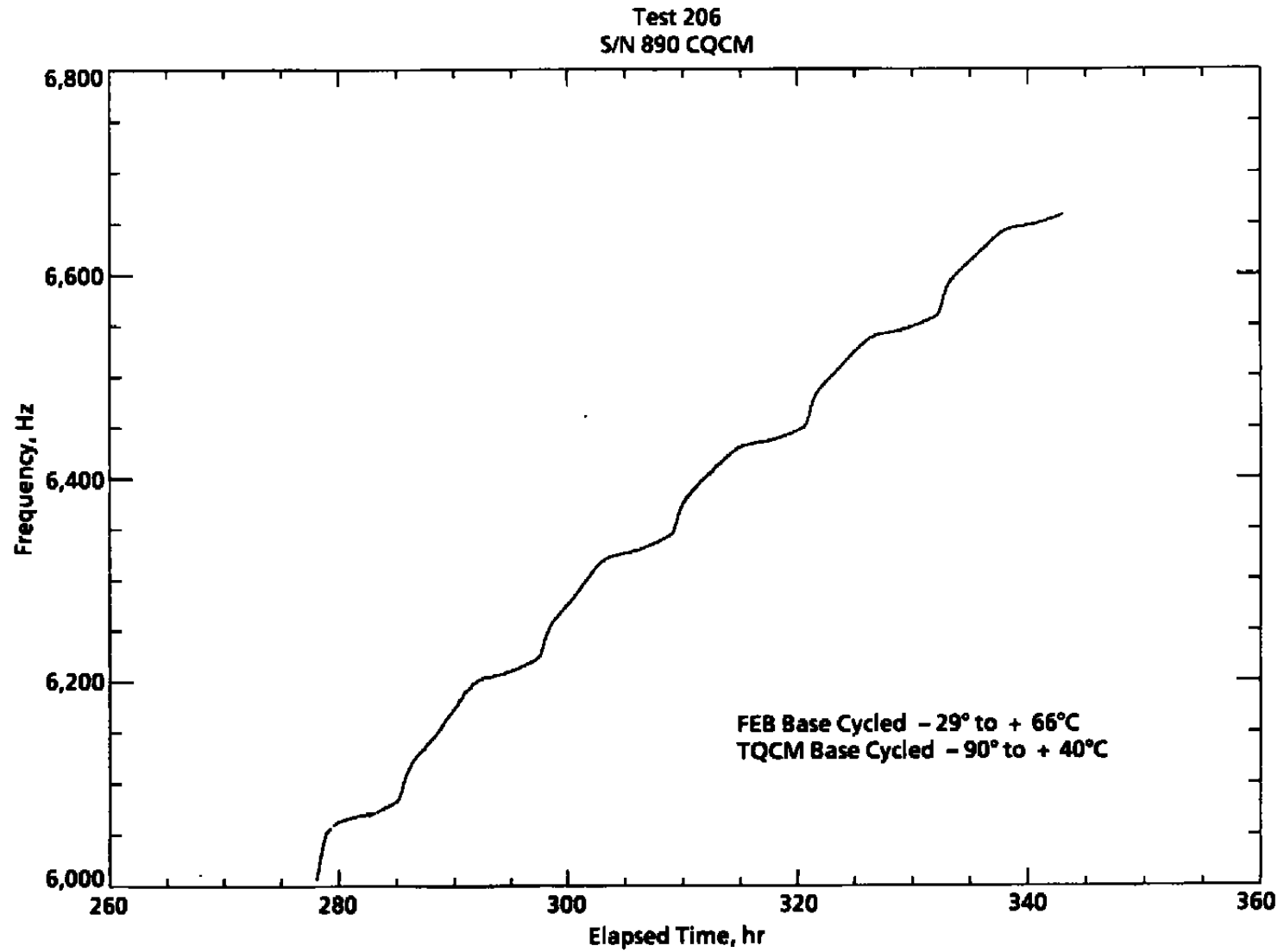
**b. TQCM S/N 3**  
**Figure 13. Continued.**



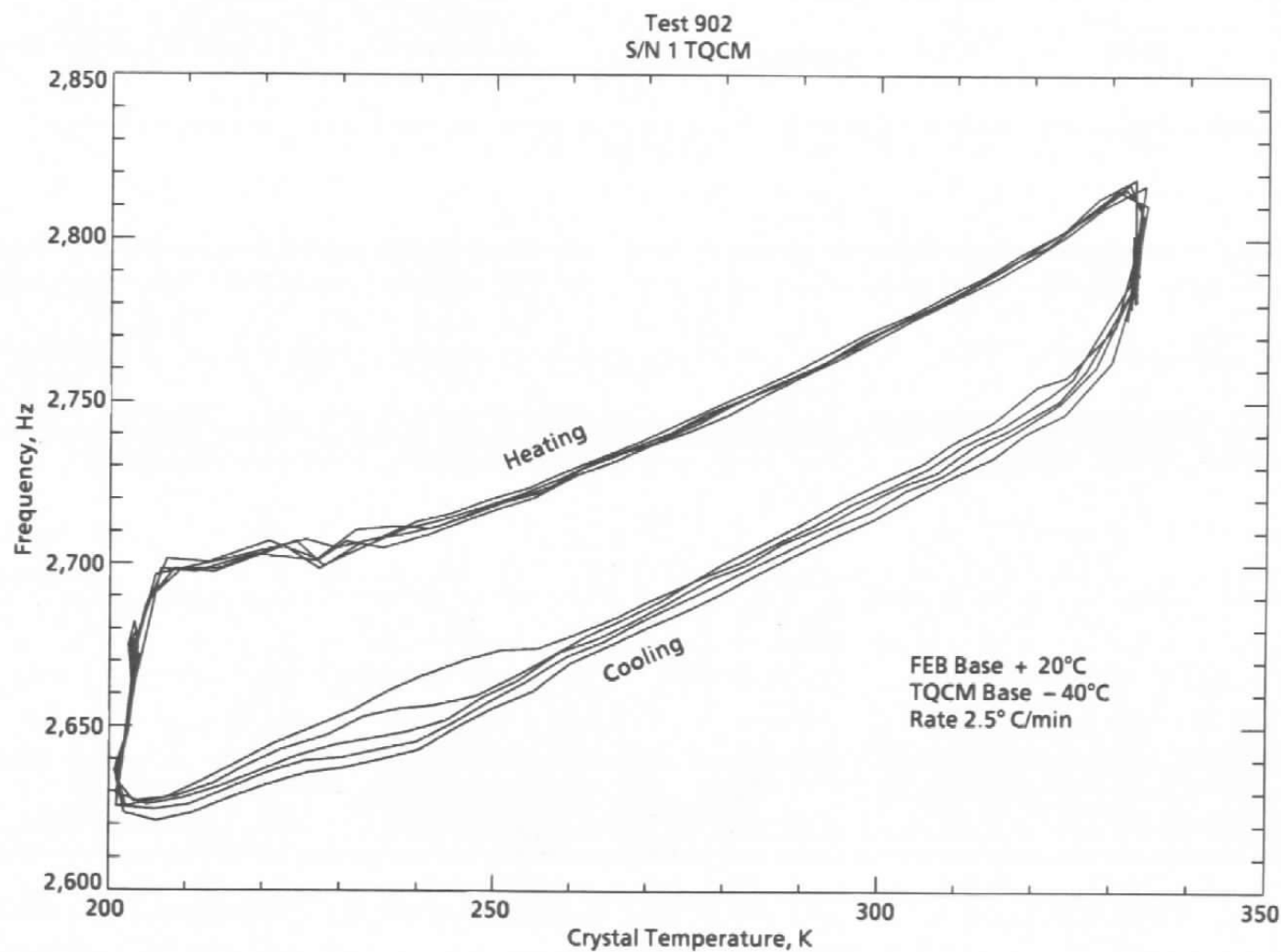
c. TQCM S/N 5  
Figure 13. Continued.



d. TQCM S/N 6  
Figure 13. Continued.

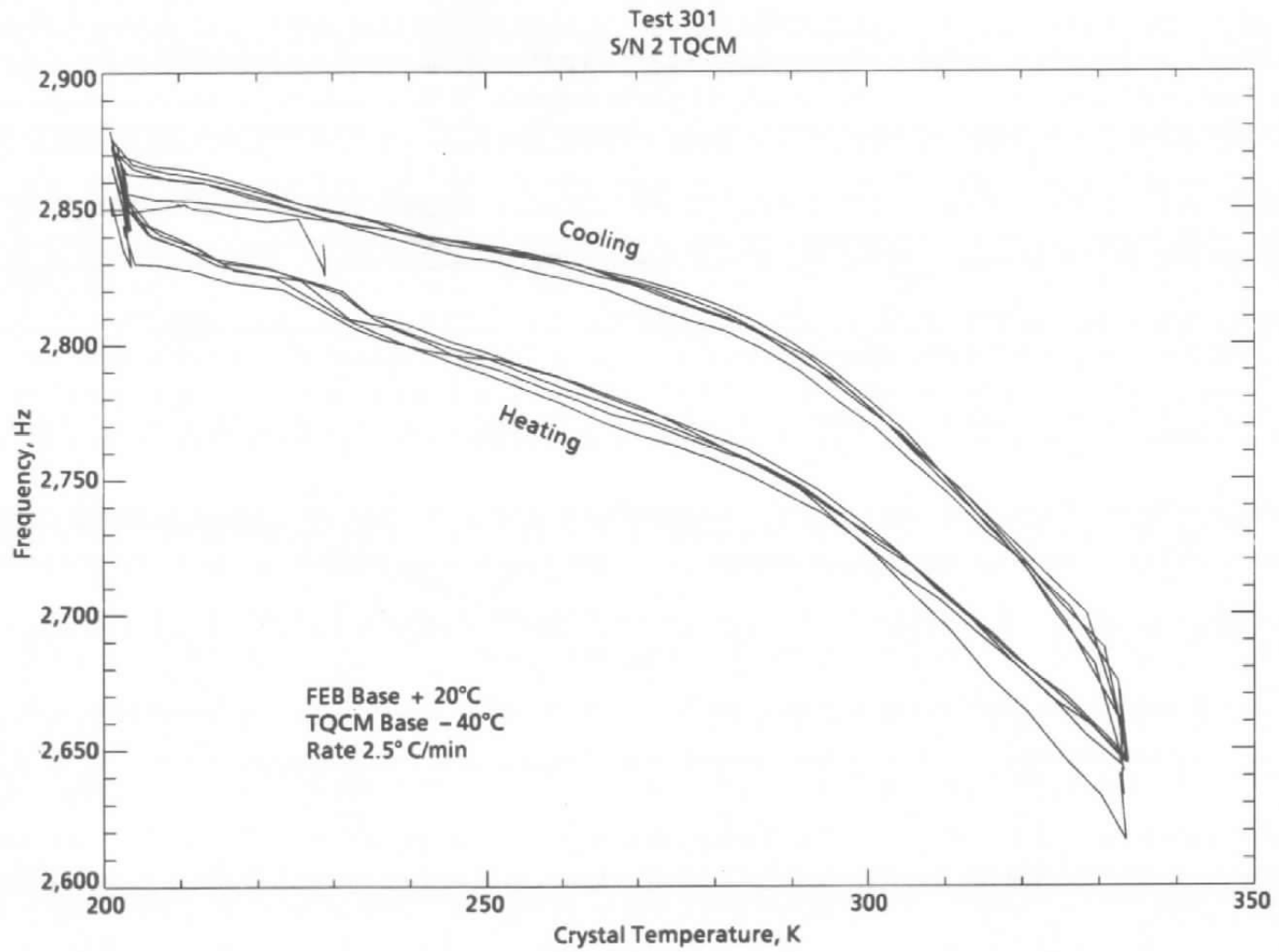


c. CQCM S/N 890  
Figure 13. Concluded.

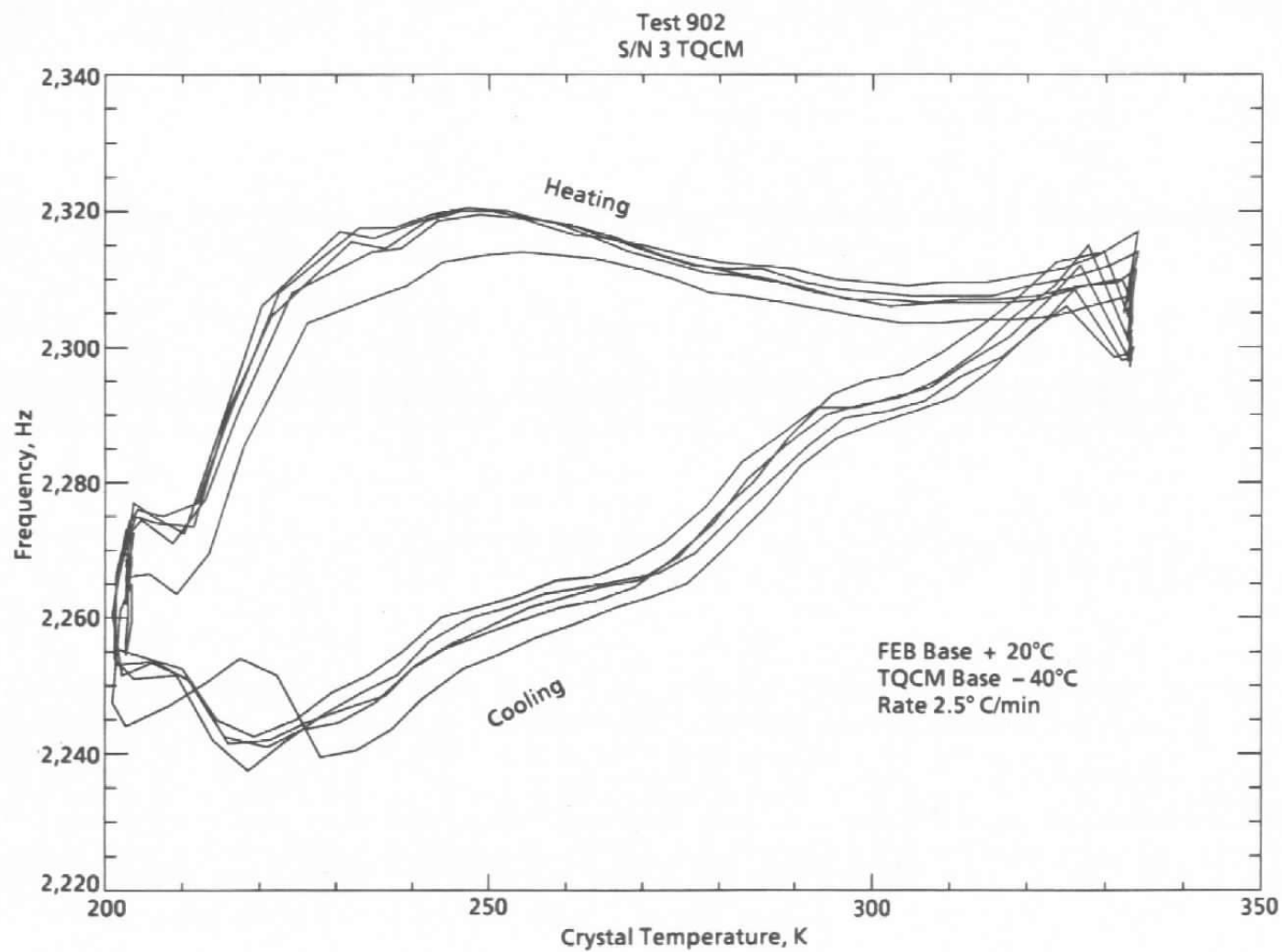


a. TQCM S/N 1

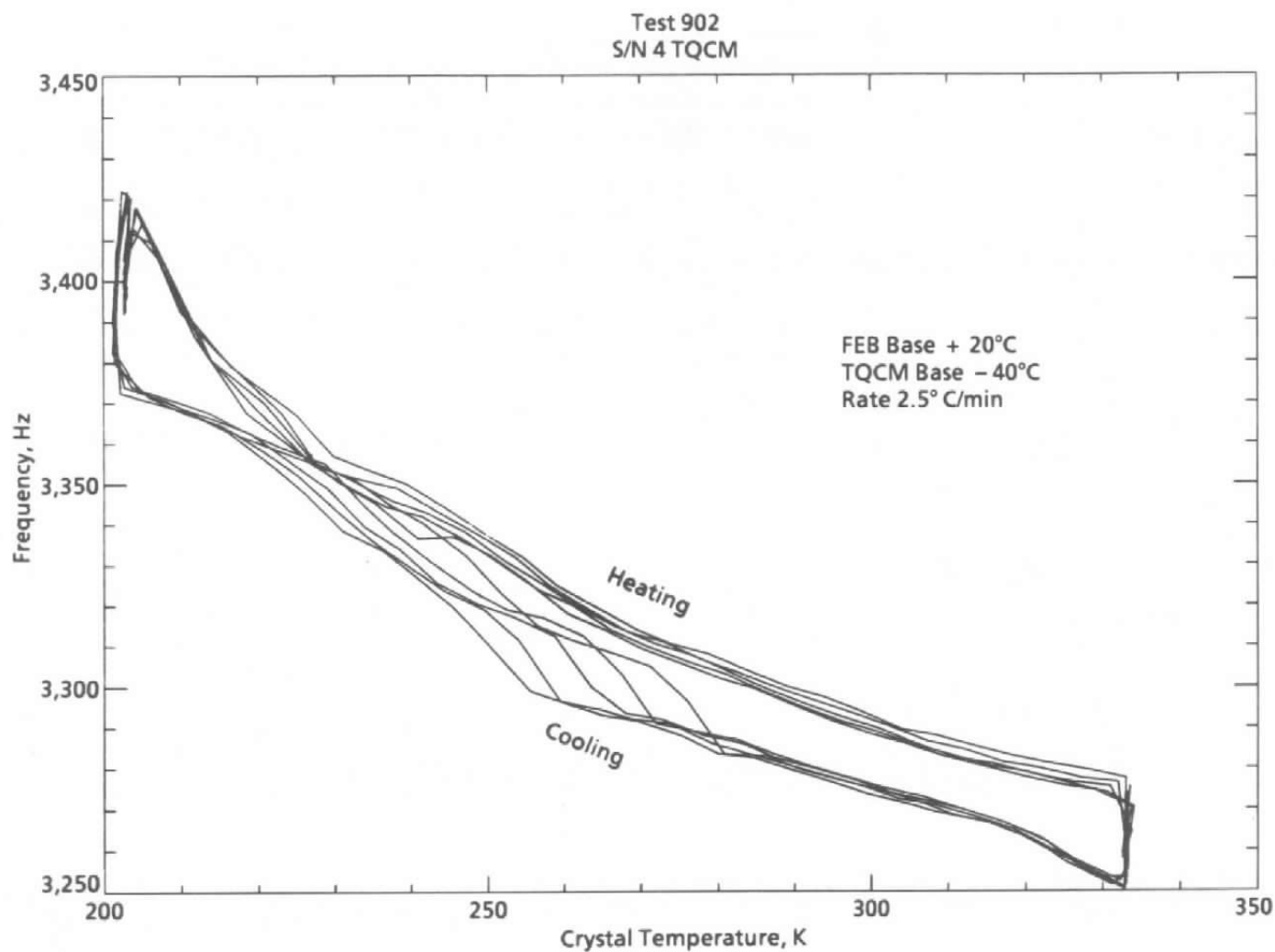
Figure 14. Frequency variation of TQCMs with crystal temperature  
(TQCM Base - 40°C).



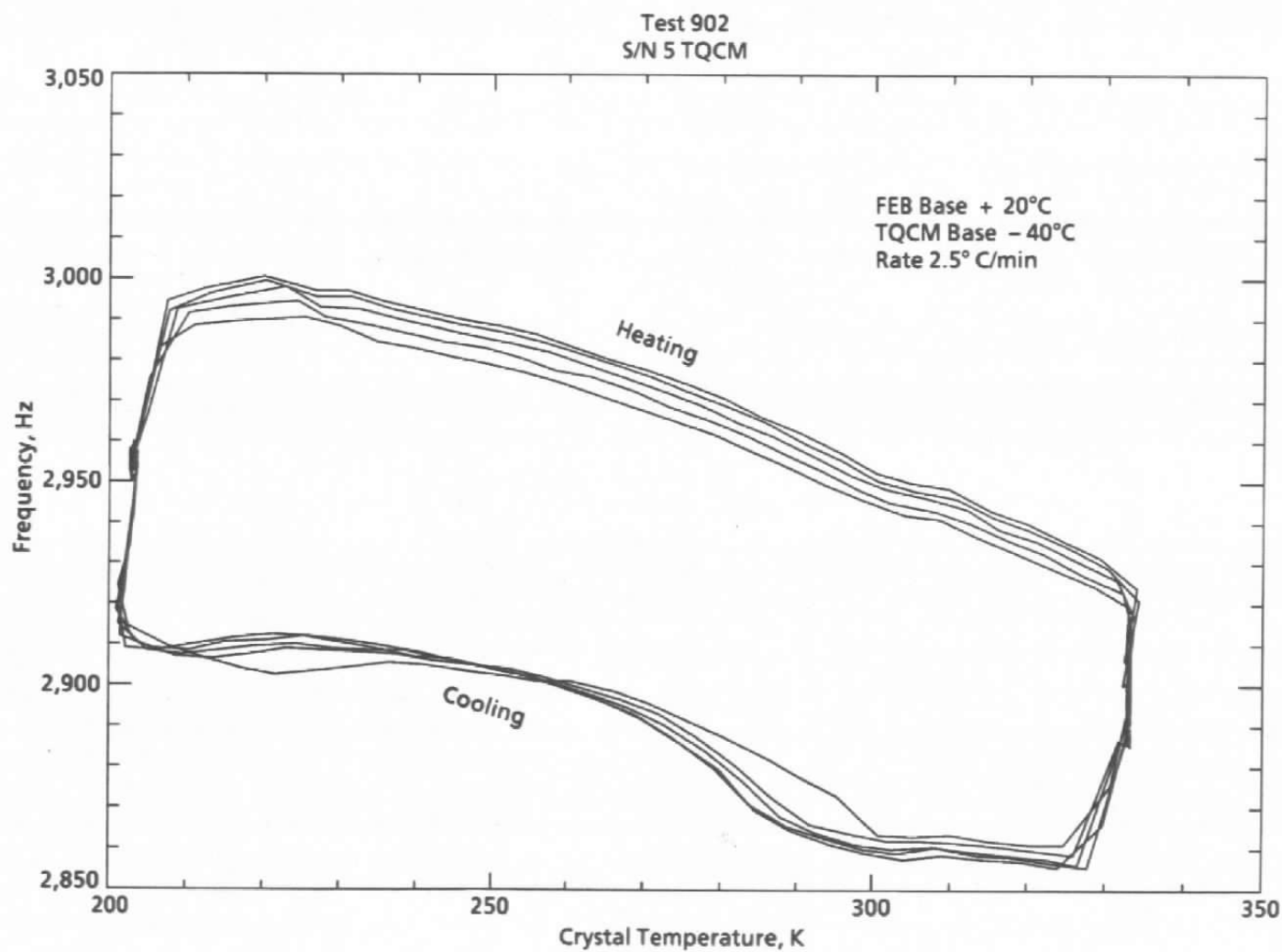
b. TQCM S/N 2  
Figure 14. Continued.



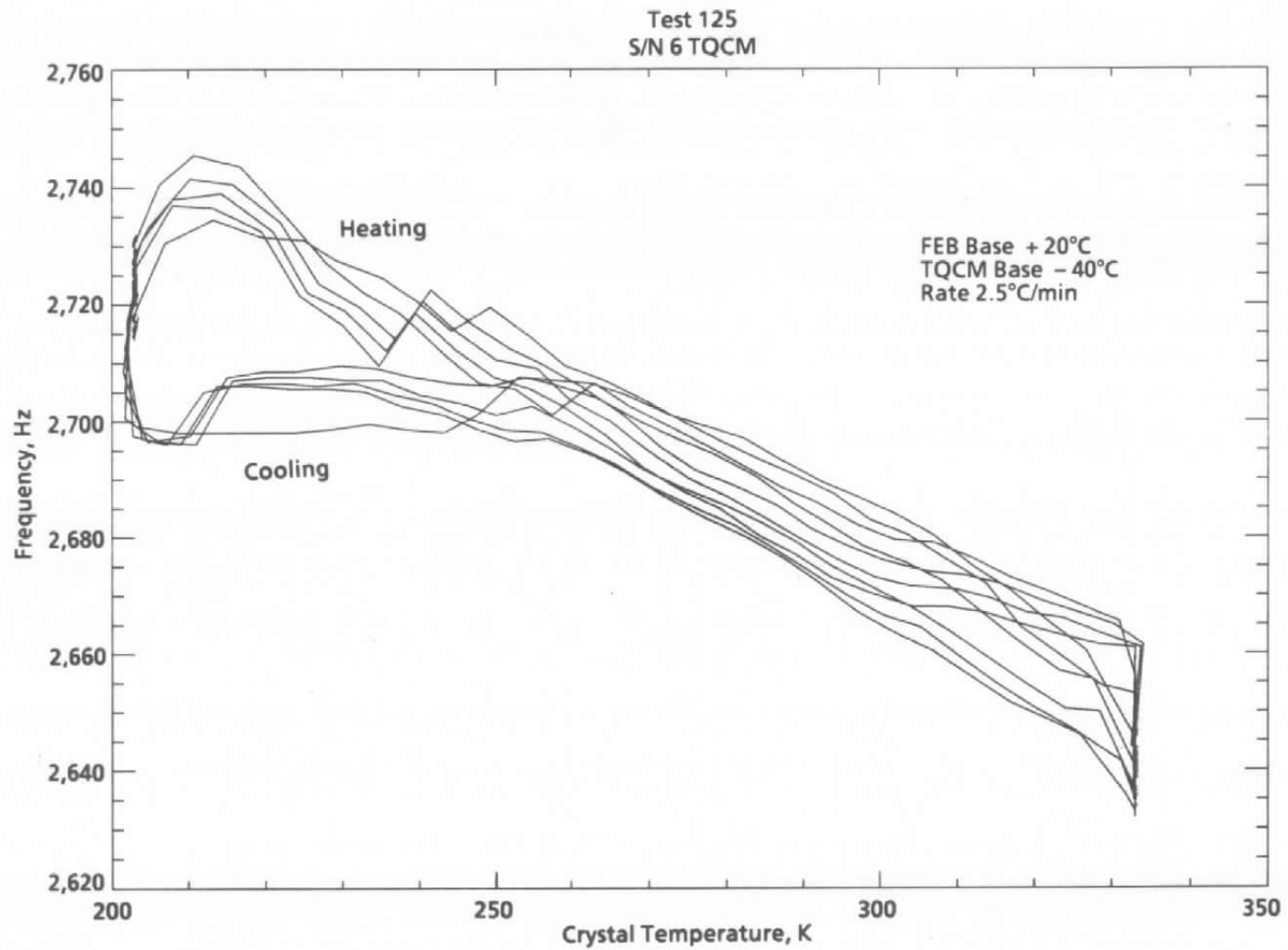
c. TQCM S/N 3  
Figure 14. Continued.



d. TQCM S/N 4  
Figure 14. Continued.

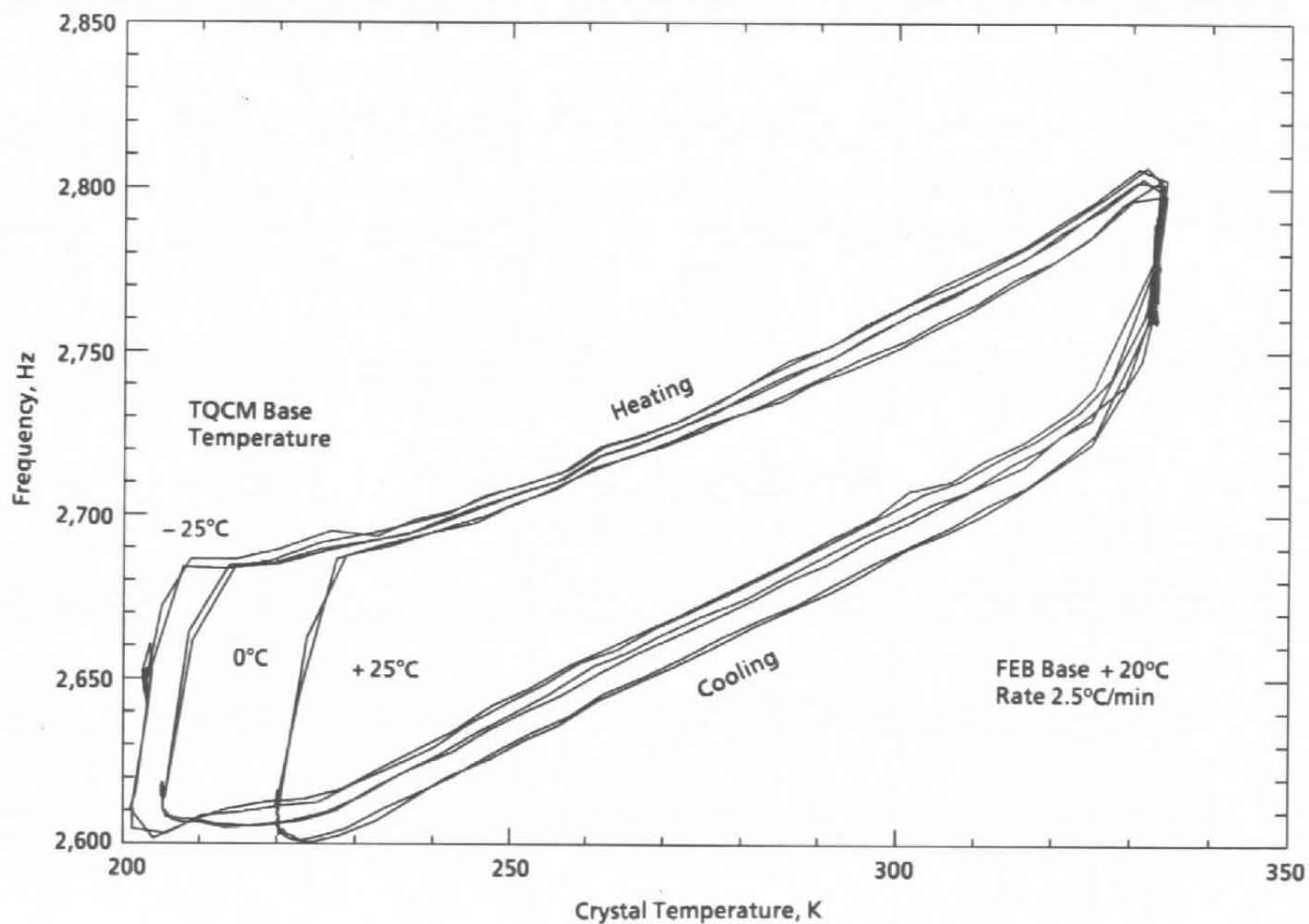


e. TQCM S/N 5  
Figure 14. Continued.



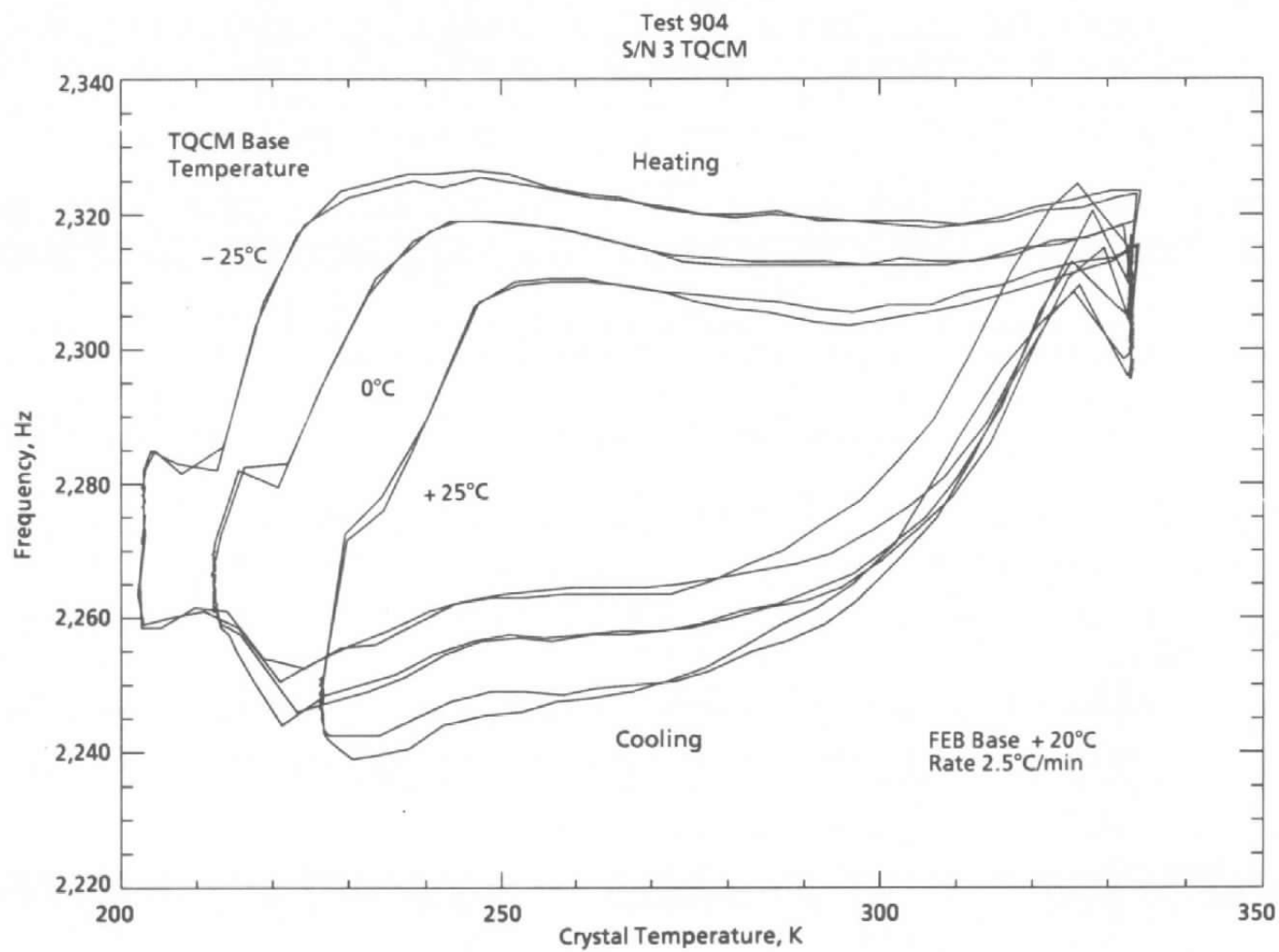
f. TQCM S/N 6  
Figure 14. Concluded.

Test 904  
S/N 1 TQCM



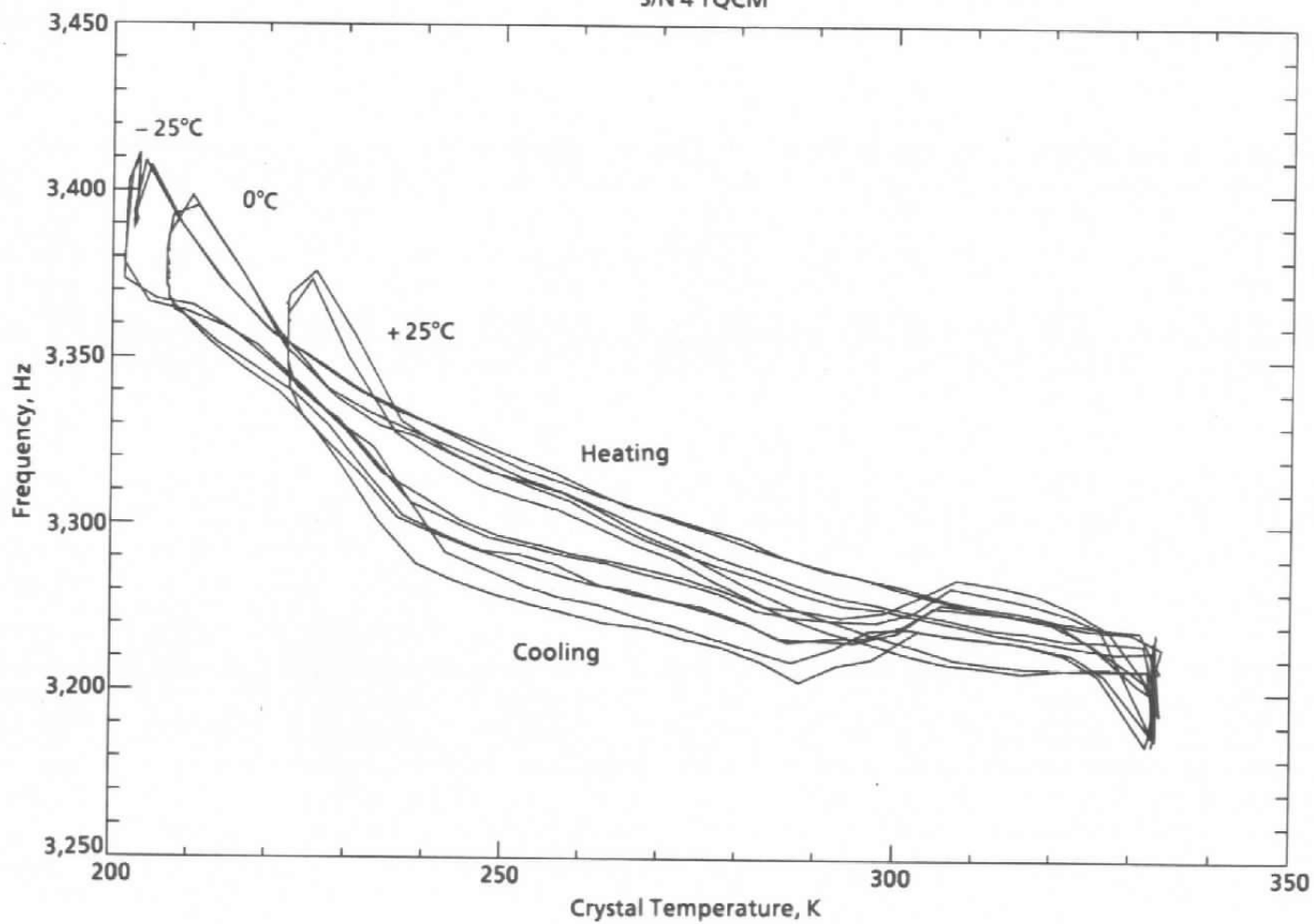
a. TQCM S/N 1

Figure 15. Frequency variation of TQCMs with crystal temperature (TQCM Base -25°, 0°, 25°C).

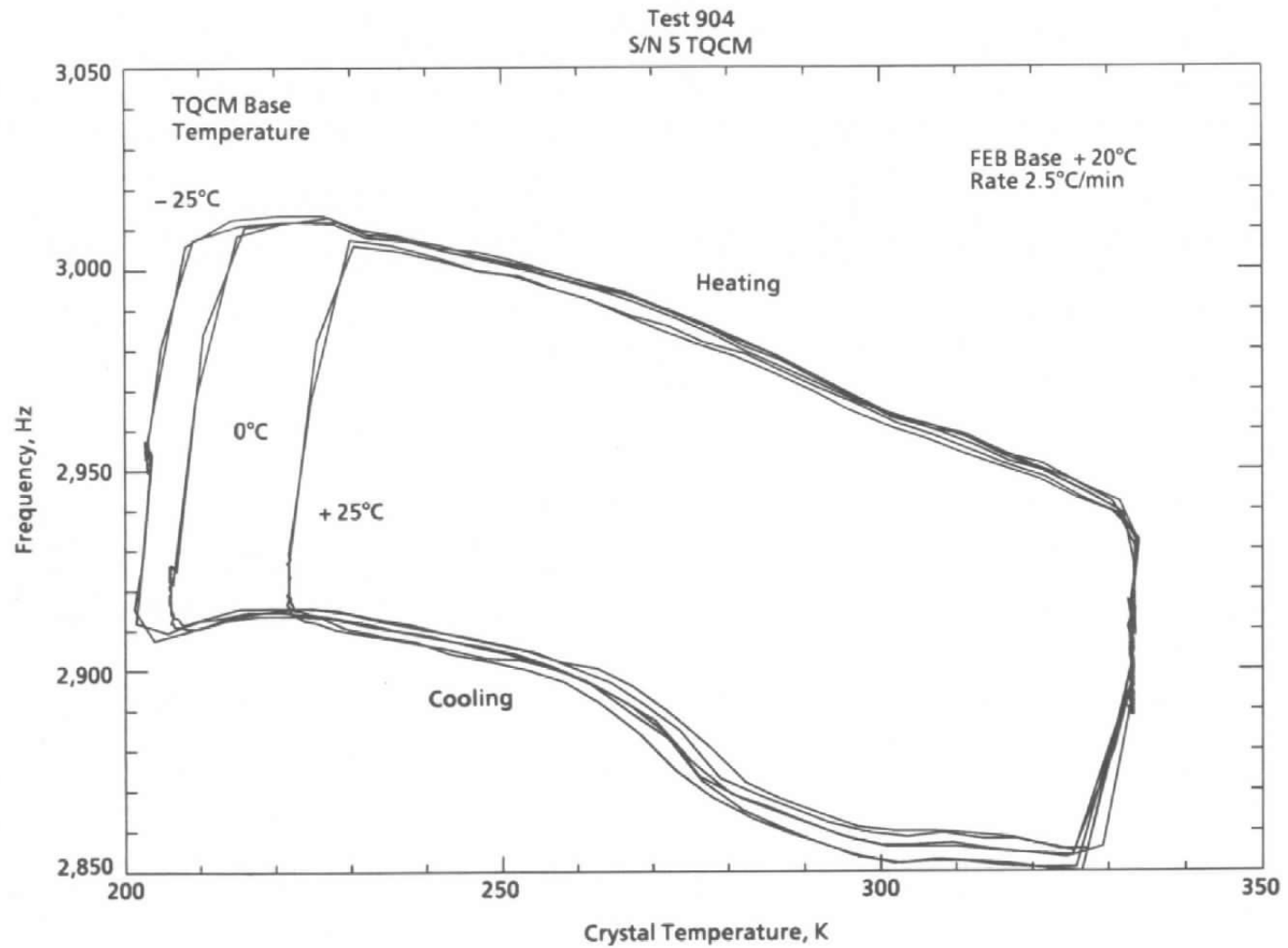


b. TQCM S/N 3  
Figure 15. Continued.

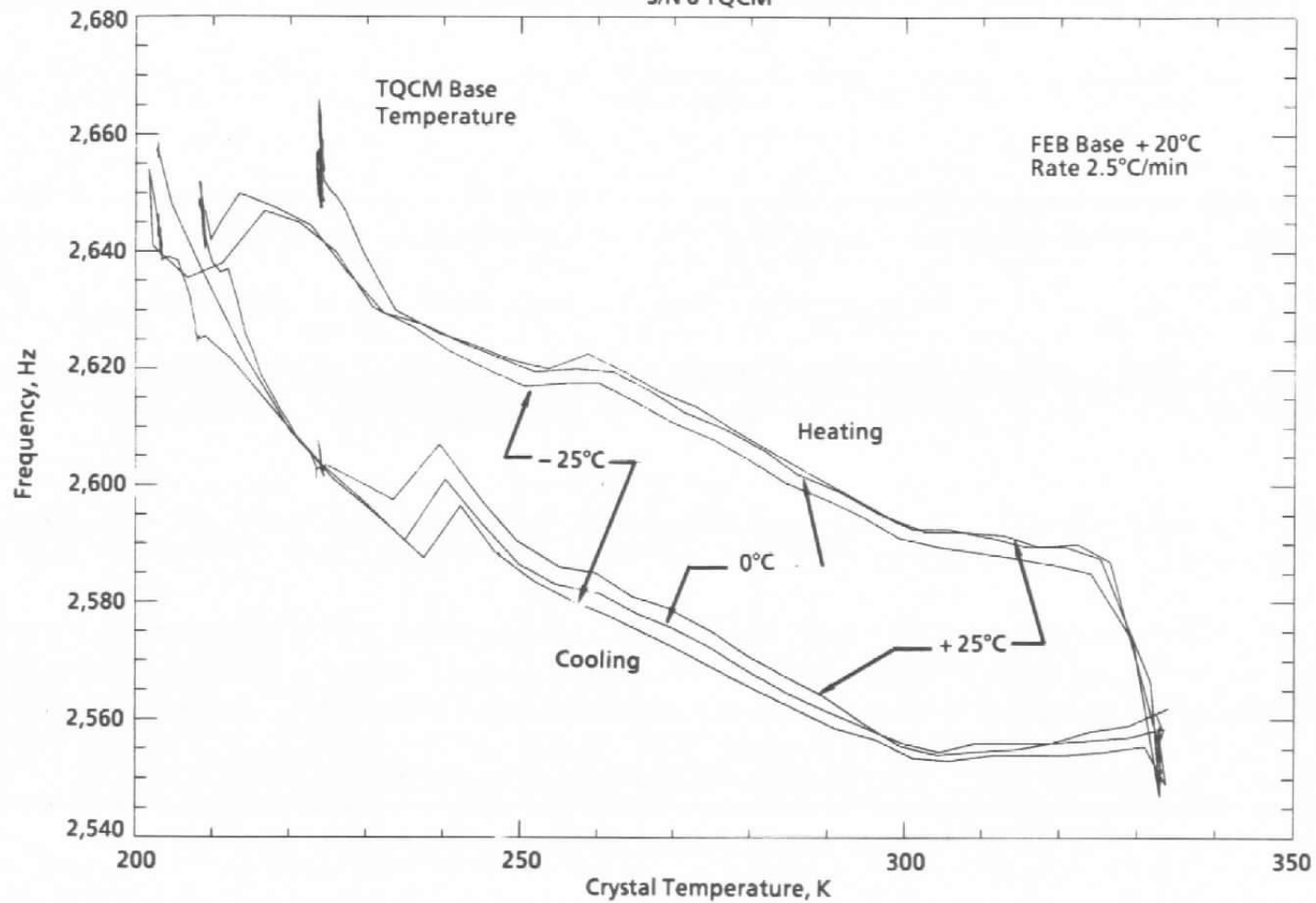
Test 904  
S/N 4 TQCM



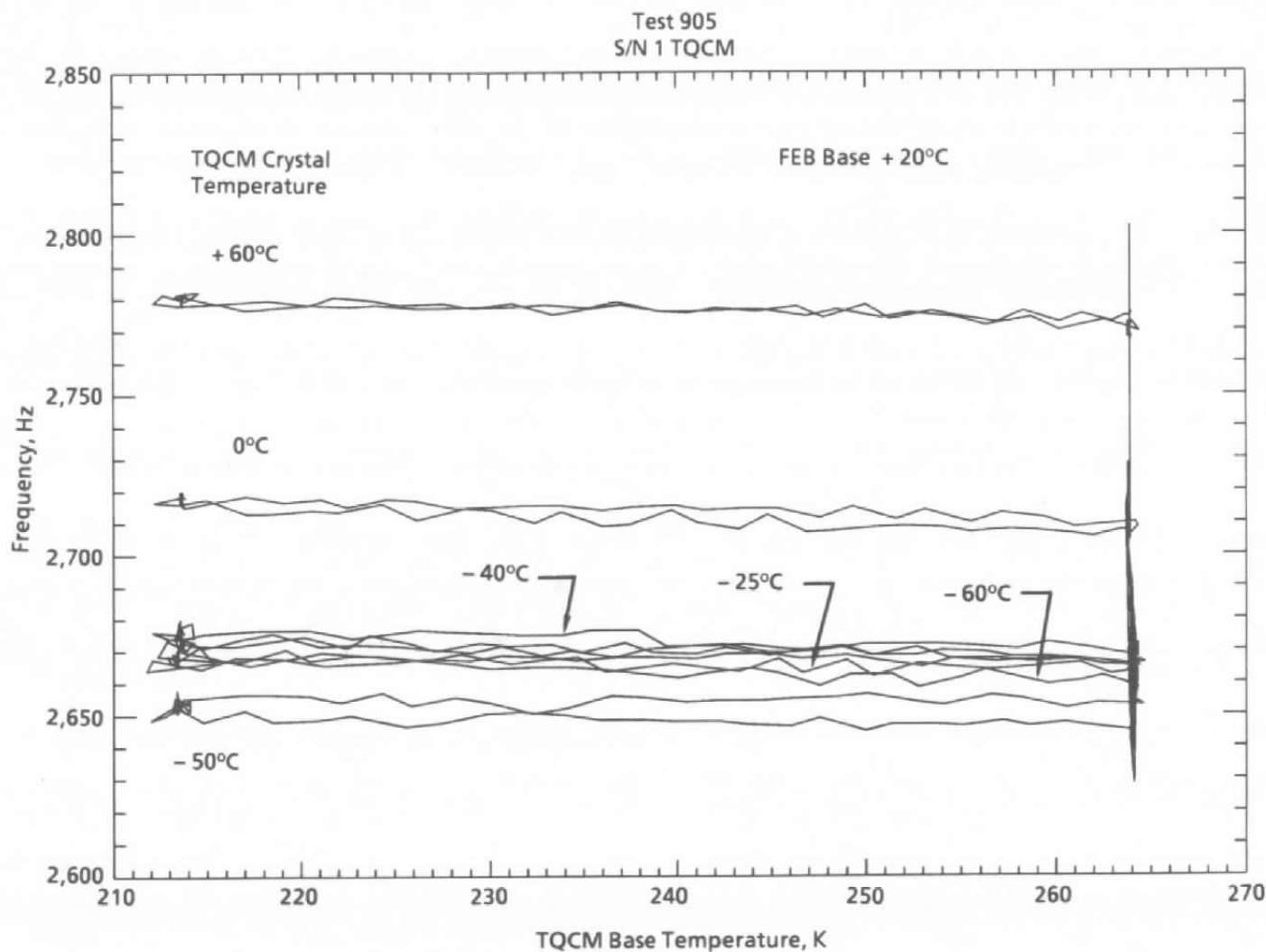
c. TQCM S/N 4  
Figure 15. Continued.



d. TQCM S/N 5  
Figure 15. Continued.



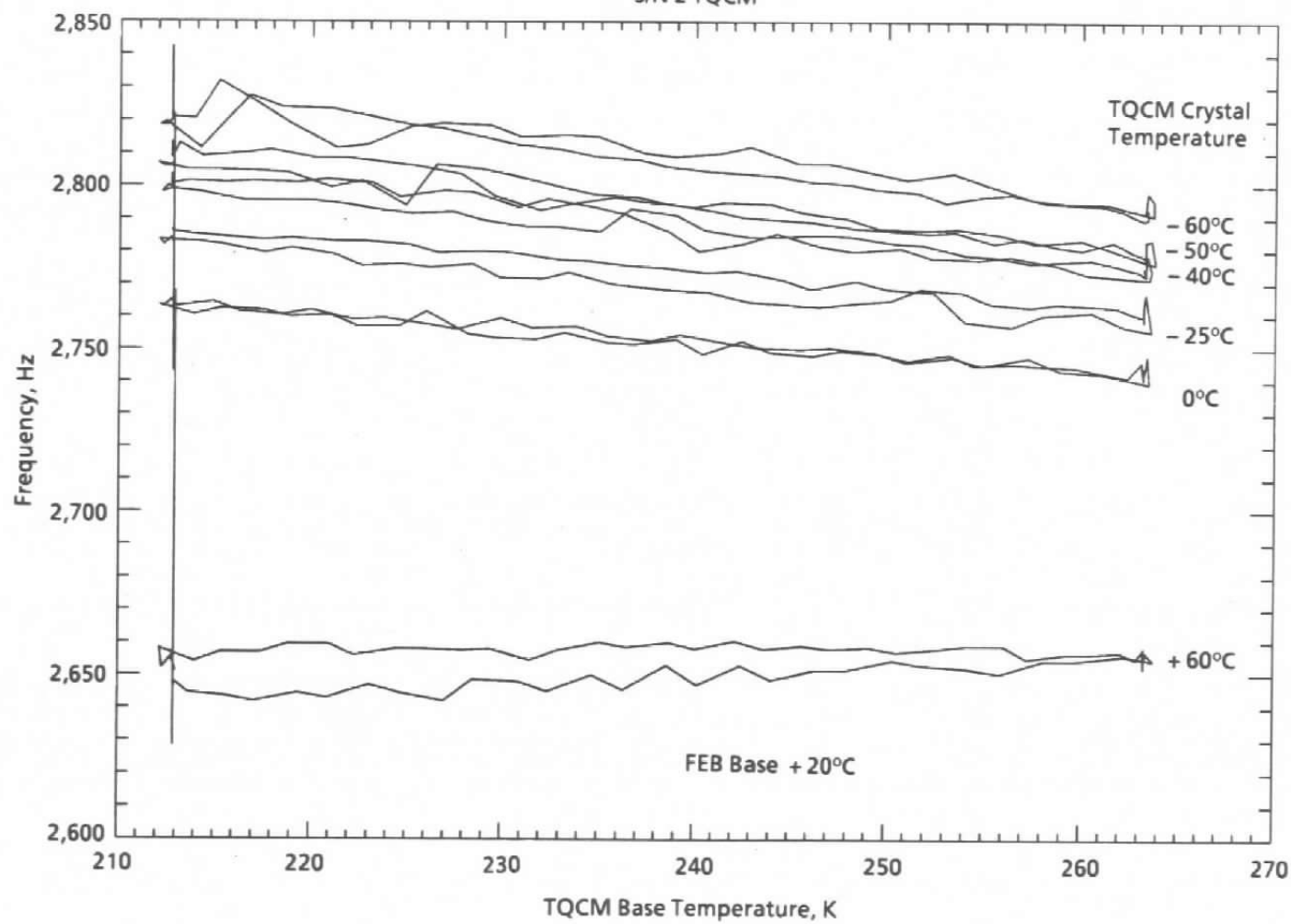
e. TQCM S/N 6  
Figure 15. Concluded.



a. TQCM S/N 1

Figure 16. Frequency variation of TQCMs with TQCM base temperature (TQCM crystal temperatures of -60, -50, -40, -25, 0, and 60°C).

Test 401  
S/N 2 TQCM



b. TQCM S/N 2  
Figure 16. Continued.

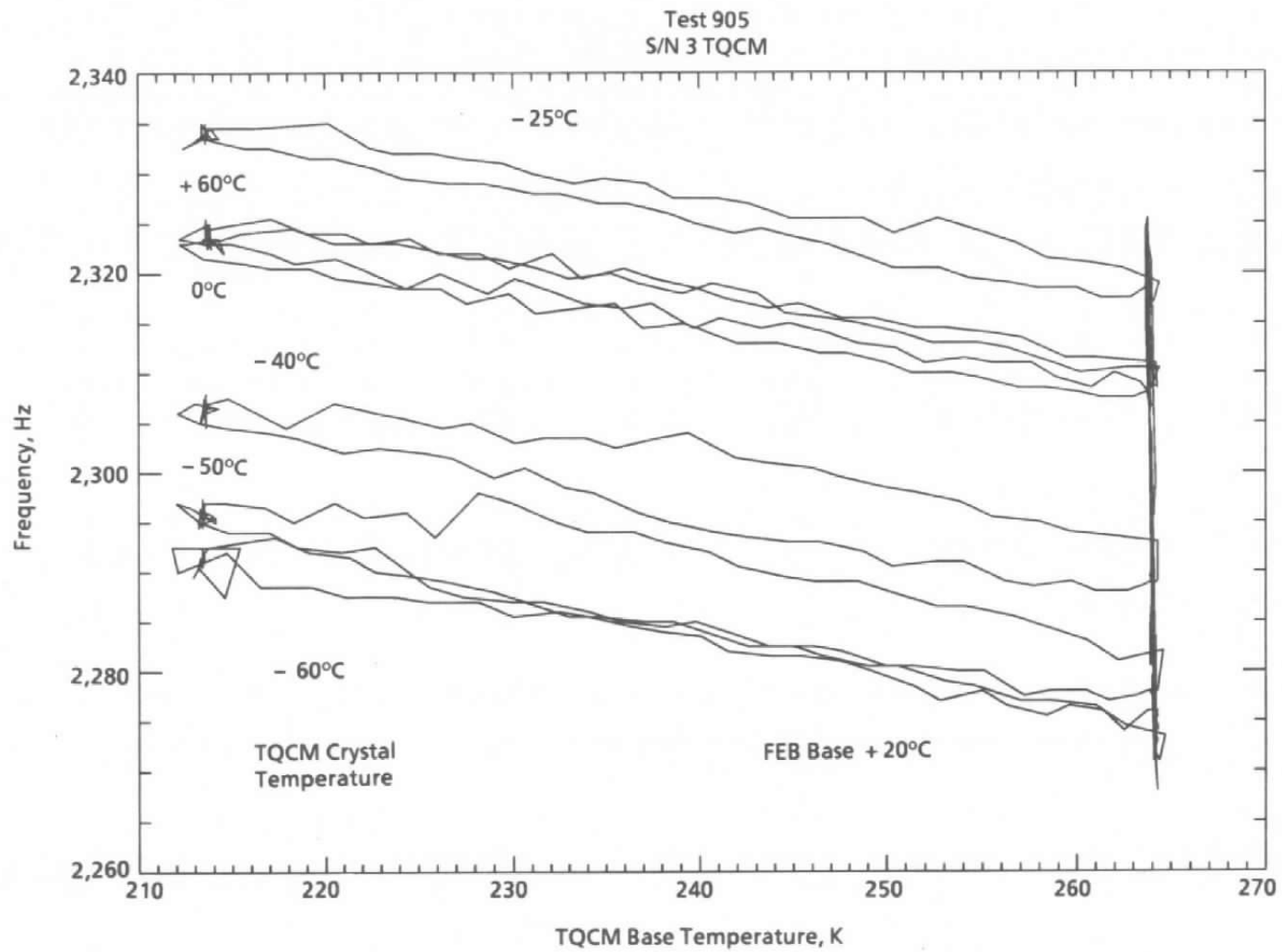
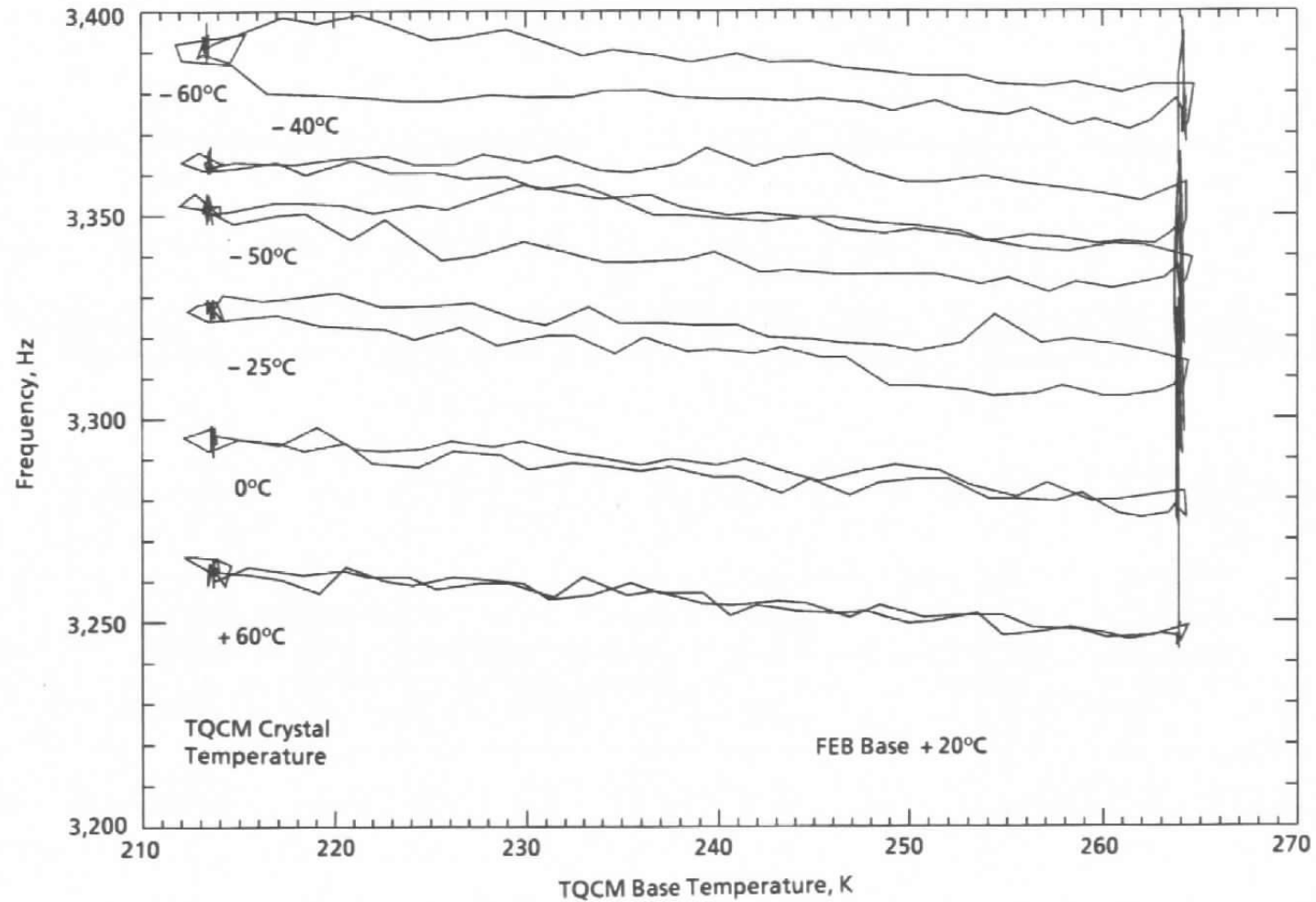
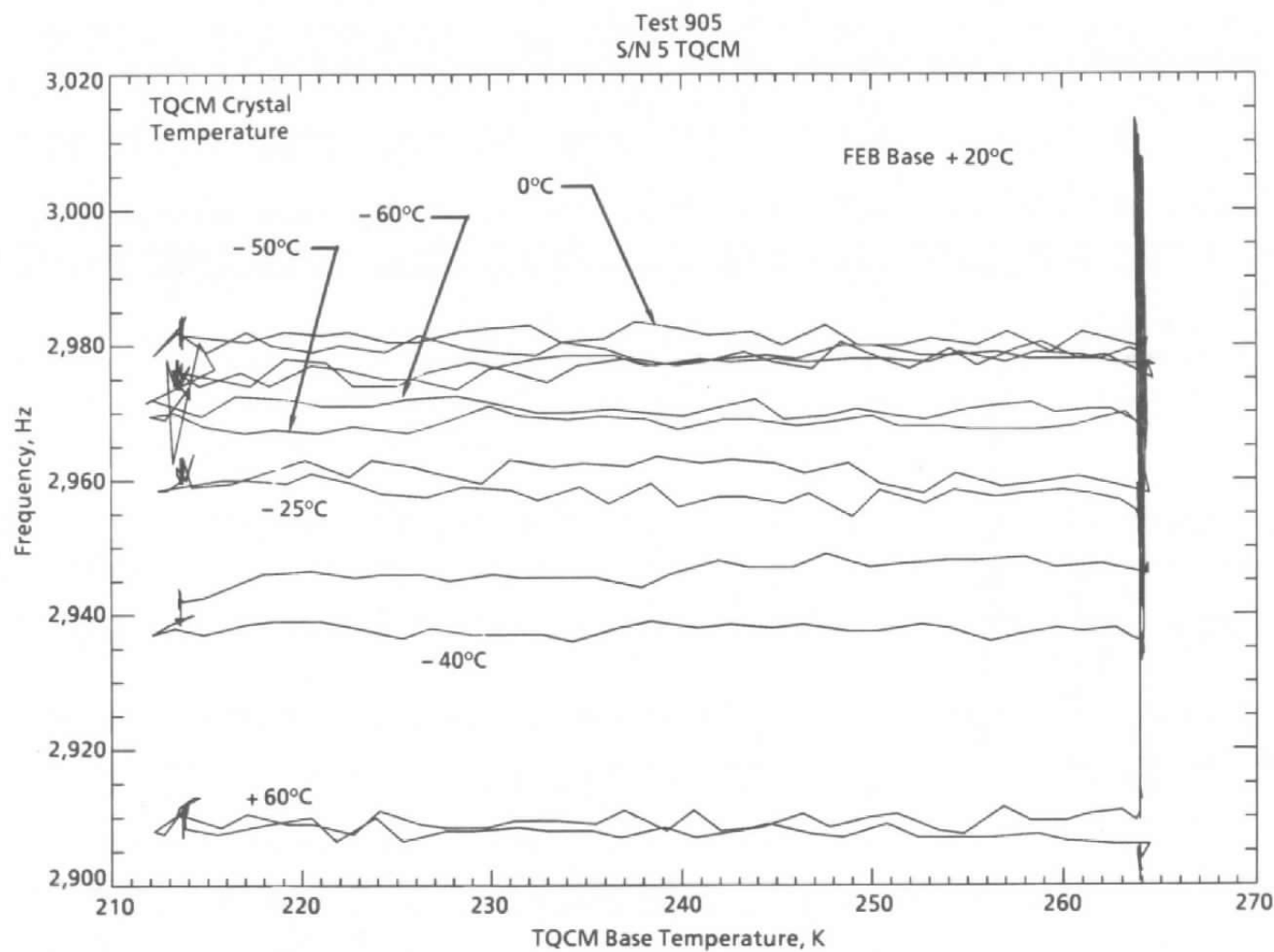


Figure 16. Continued.

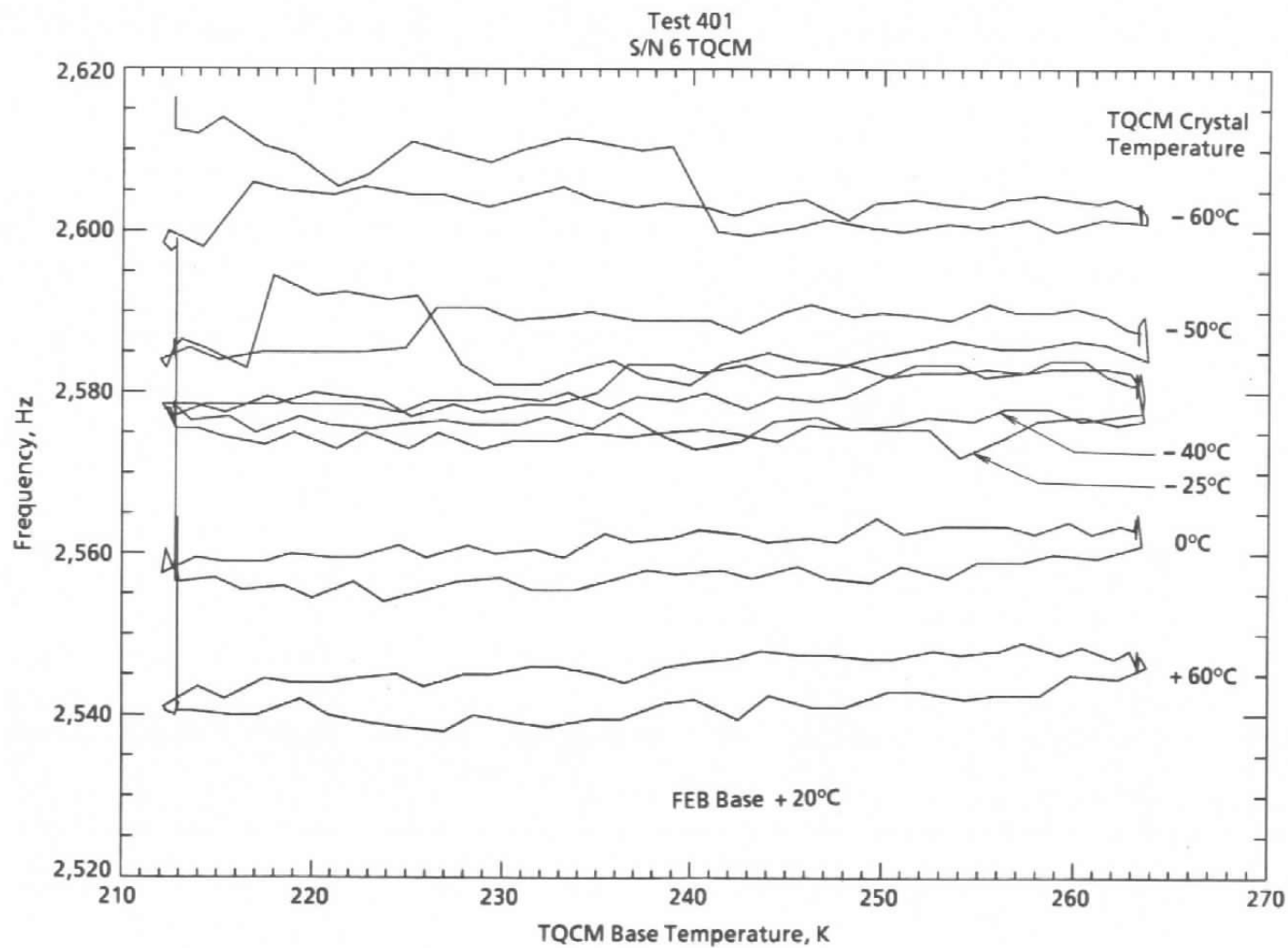
Test 905  
S/N 4 TQCM



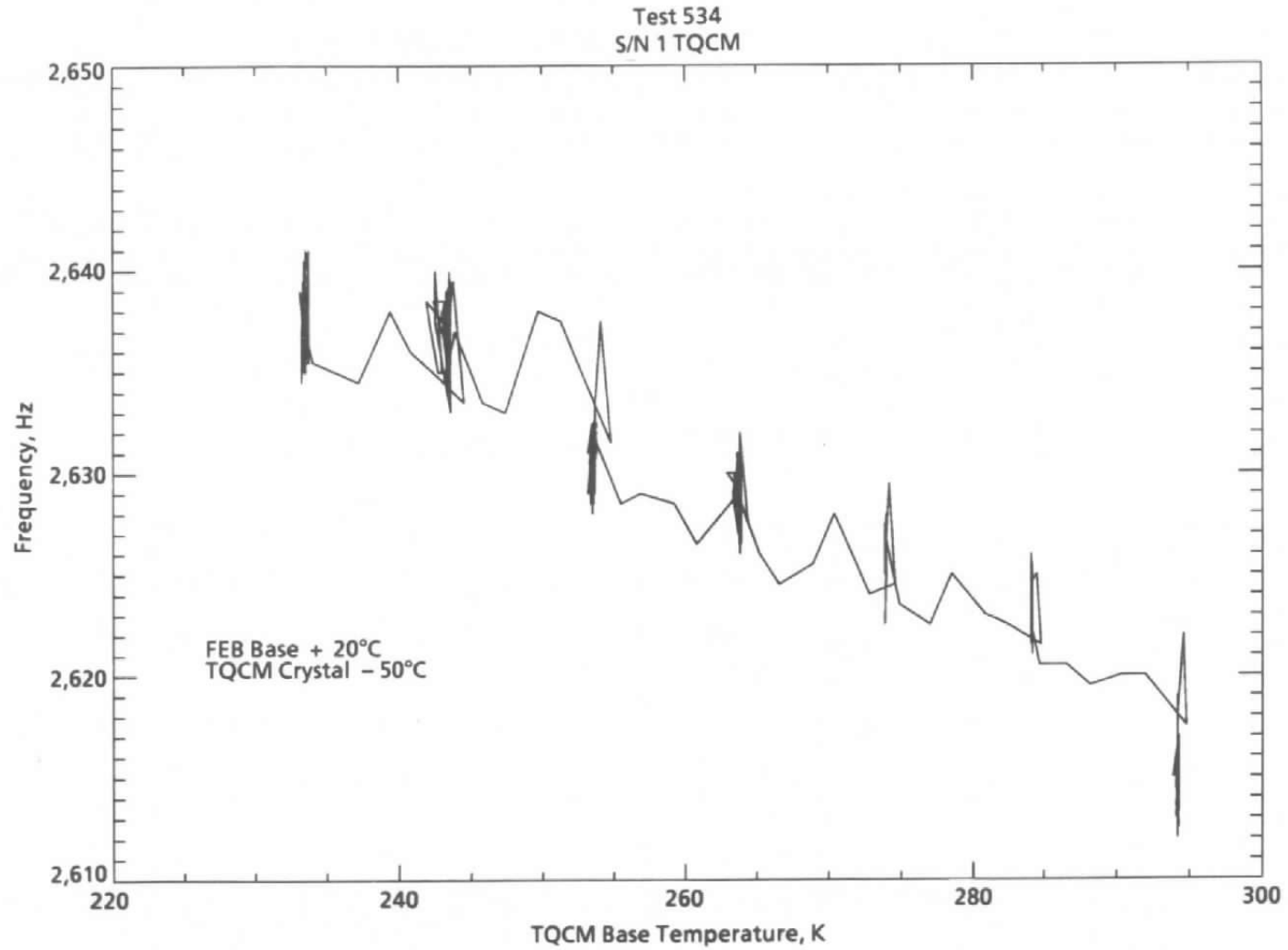
d. TQCM S/N 4  
Figure 16. Continued.



e. TQCM S/N 5  
Figure 16. Continued.

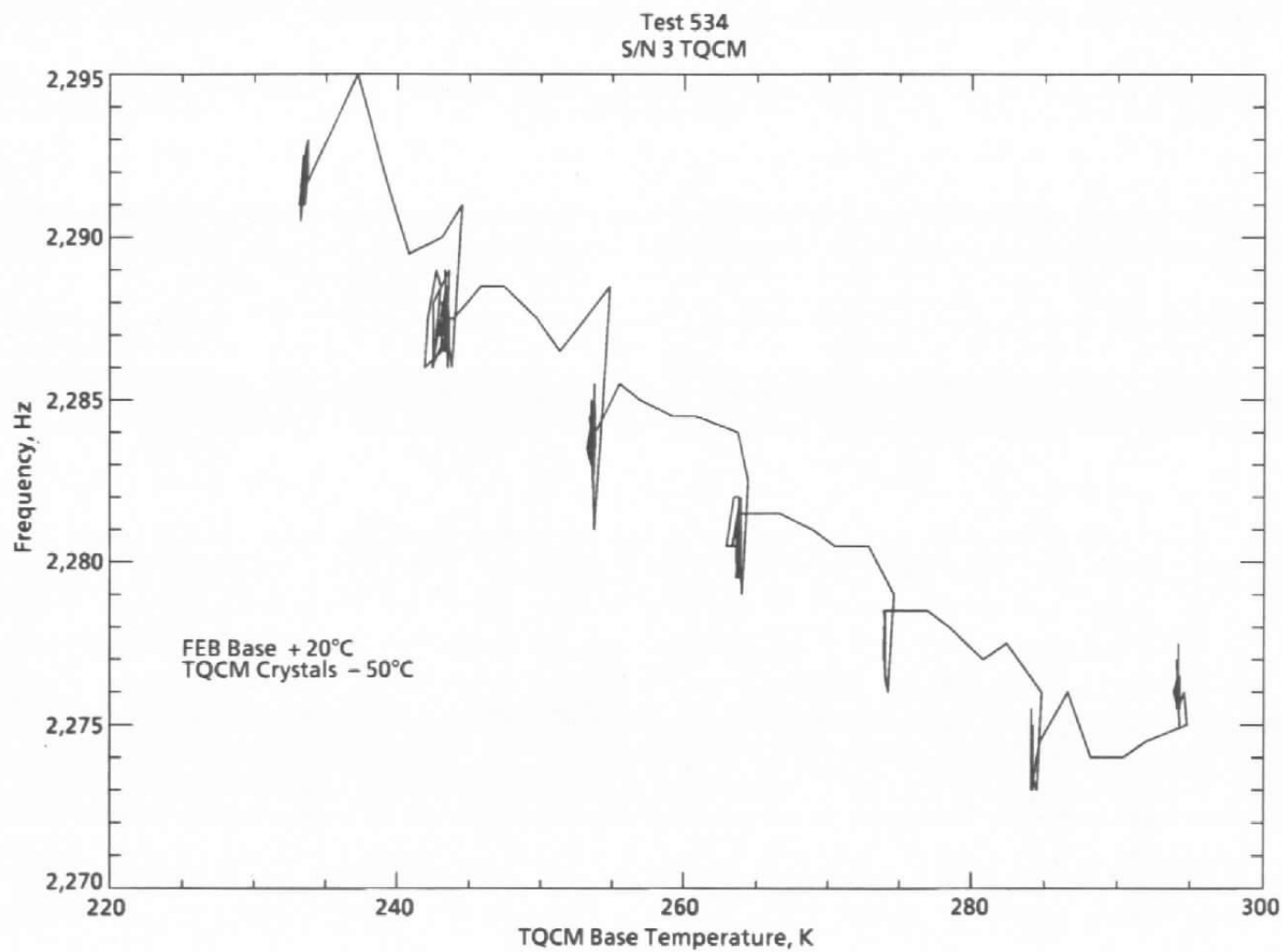


f. TQCM S/N 6  
Figure 16. Concluded.

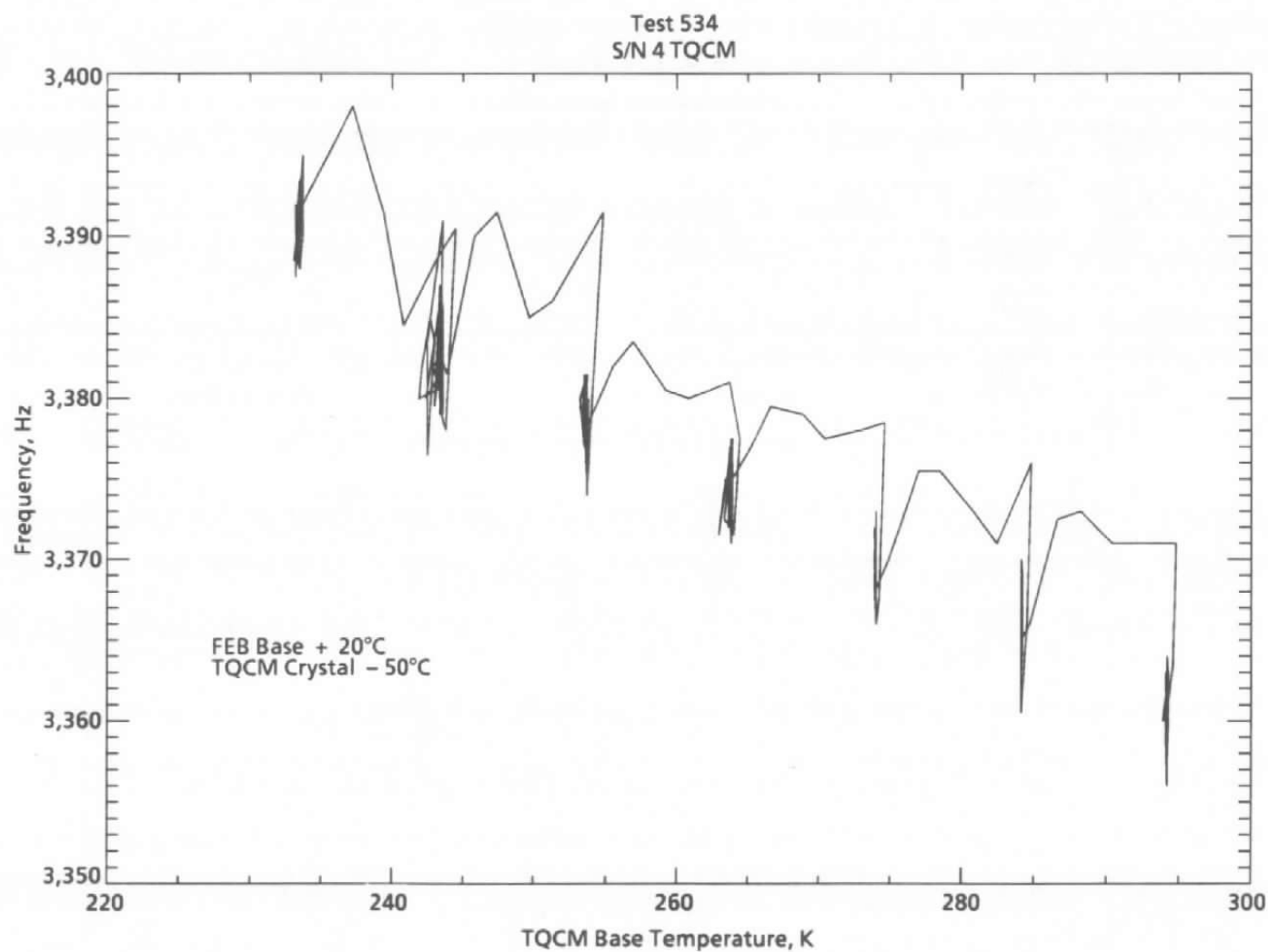


a. TQCM S/N 1

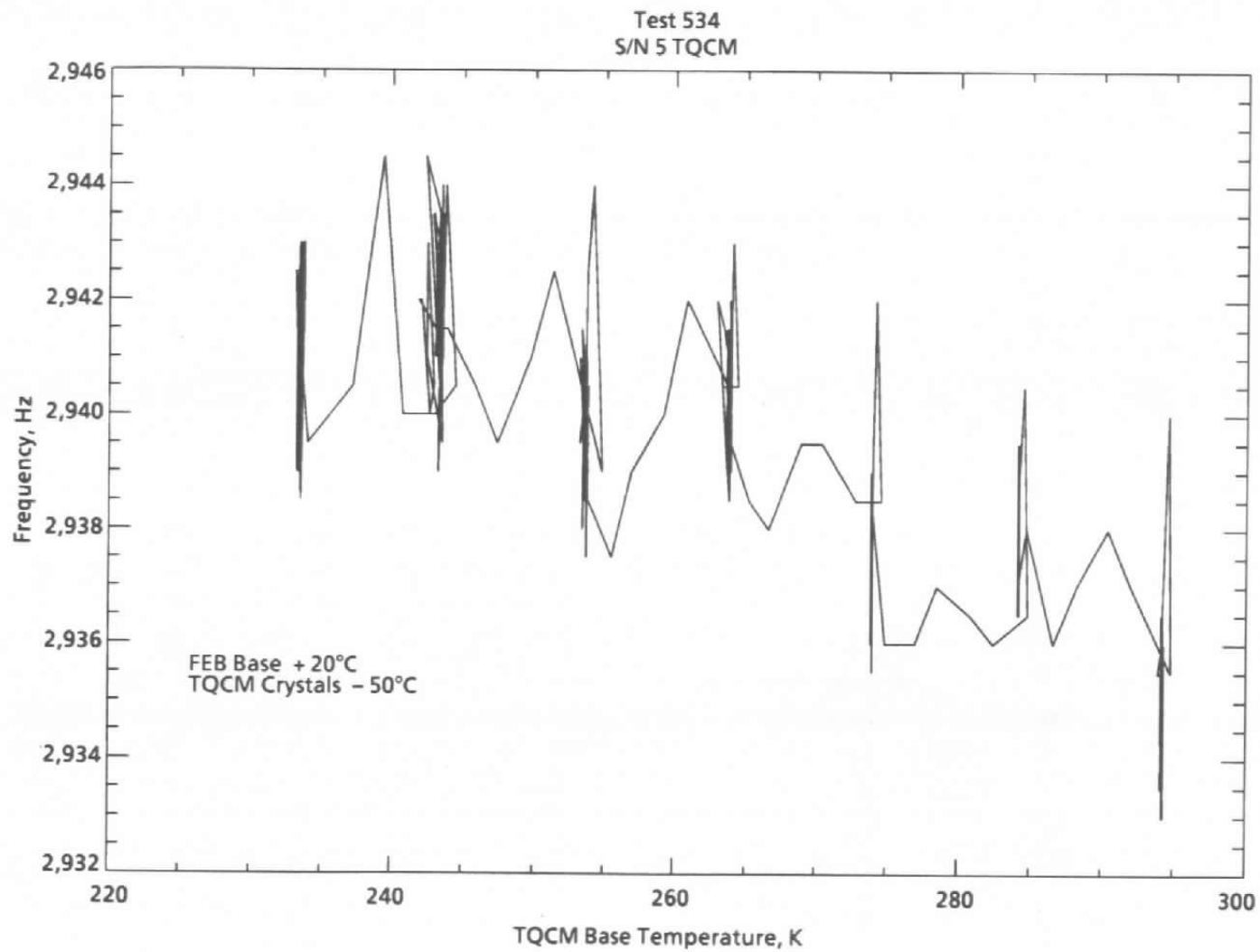
Figure 17. Frequency variation of TQCMs with TQCM base temperature  
(TQCM crystal temperatures - 50°C).



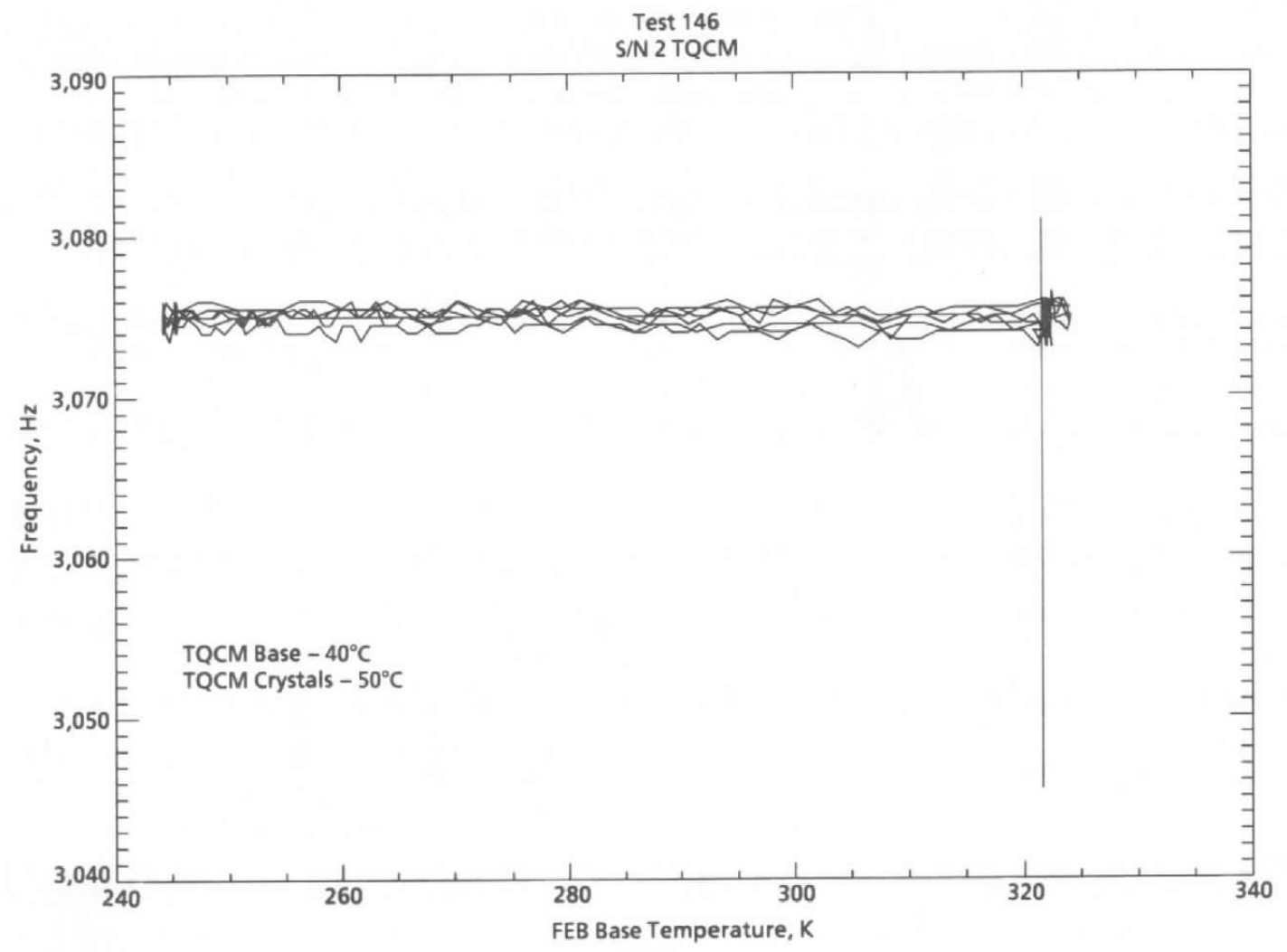
b. TQCM S/N 3  
Figure 17. Continued.



c. TQCM S/N 4  
Figure 17. Continued.

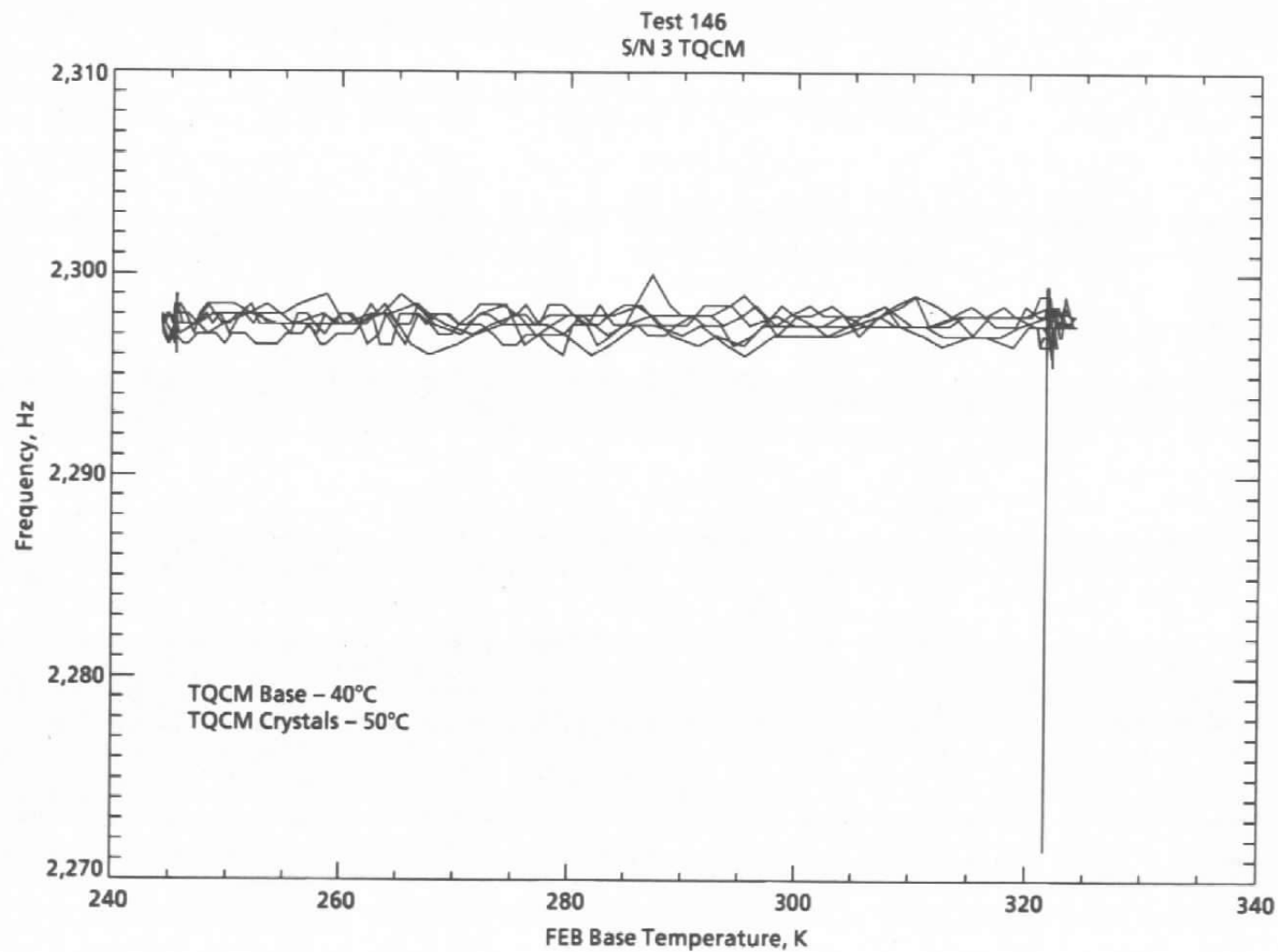


d. TQCM S/N 5  
Figure 17. Concluded.

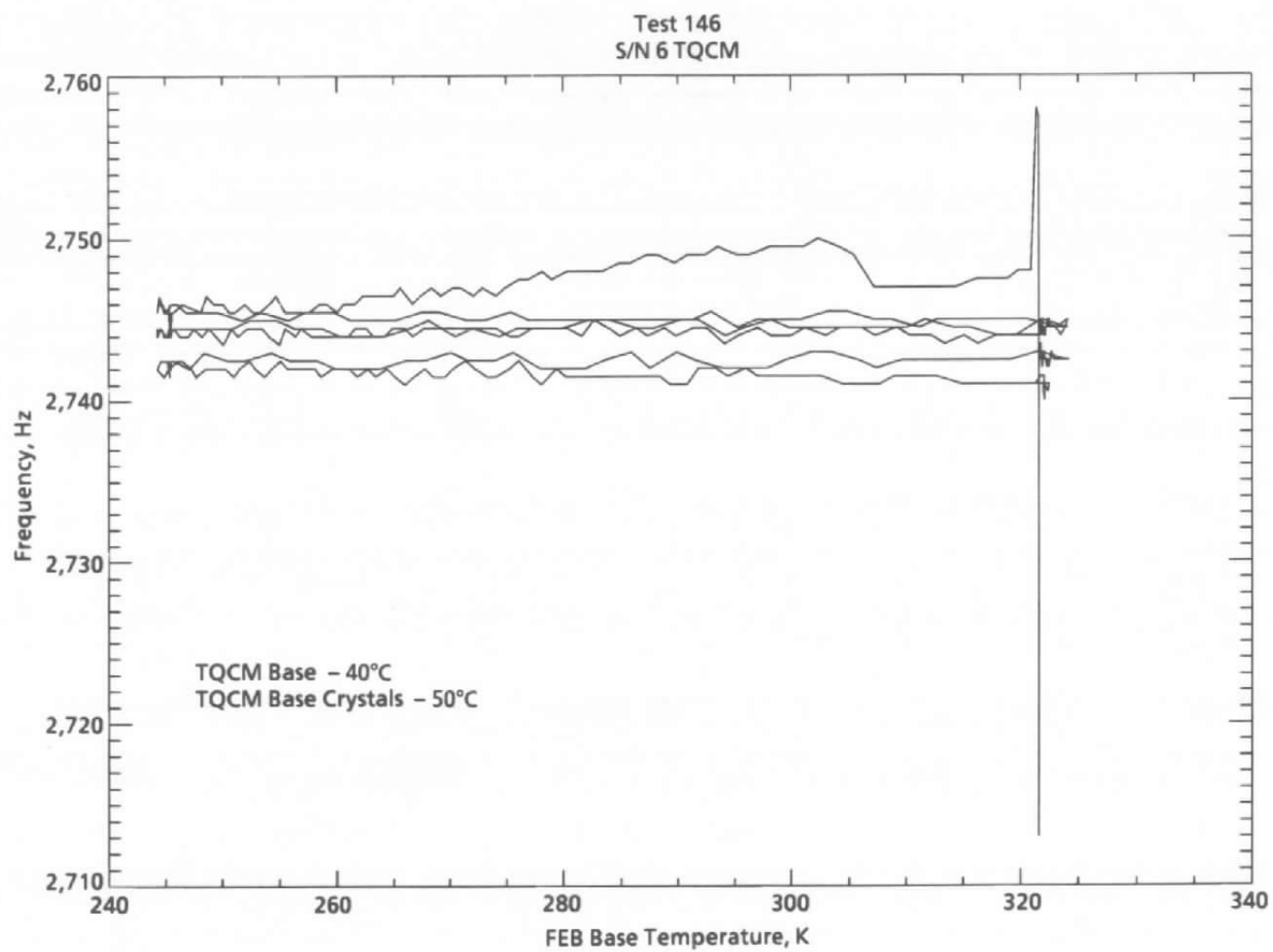


a. TQCM S/N 2

Figure 18. Frequency variation of TQCMs with FEB base temperature.



b. TQCM S/N 3  
Figure 18. Continued.



c. TQCM S/N 6  
Figure 18. Concluded.

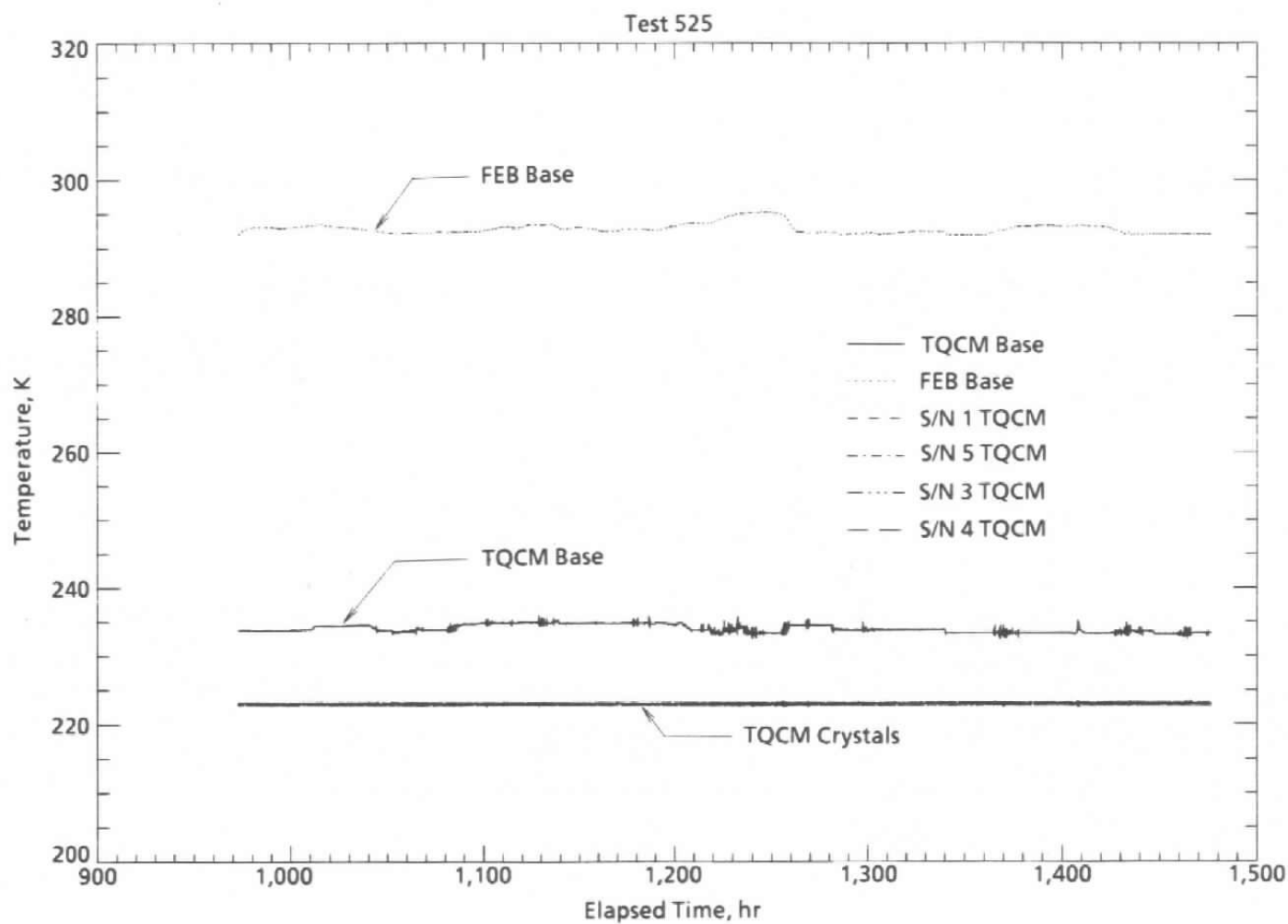
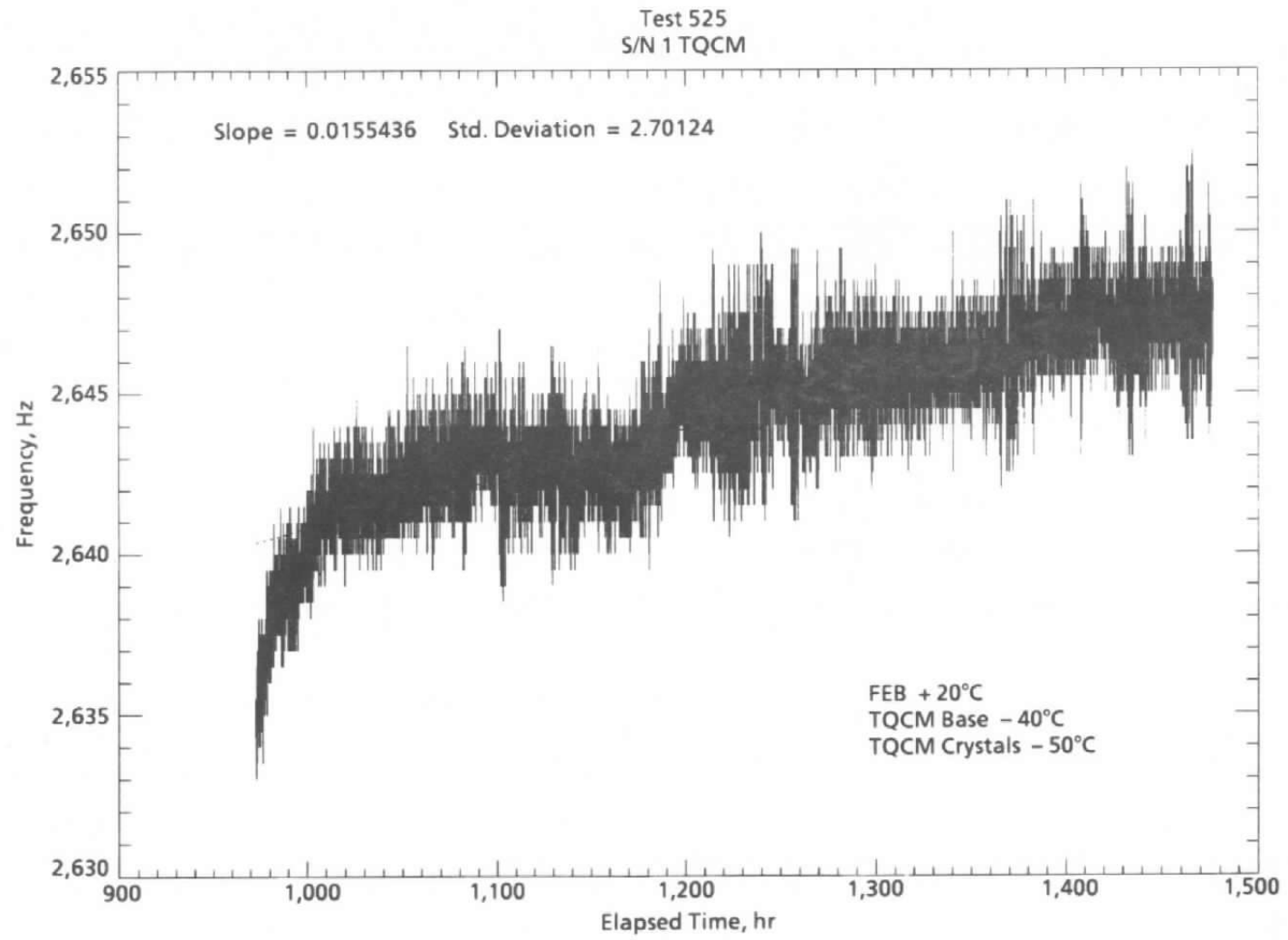
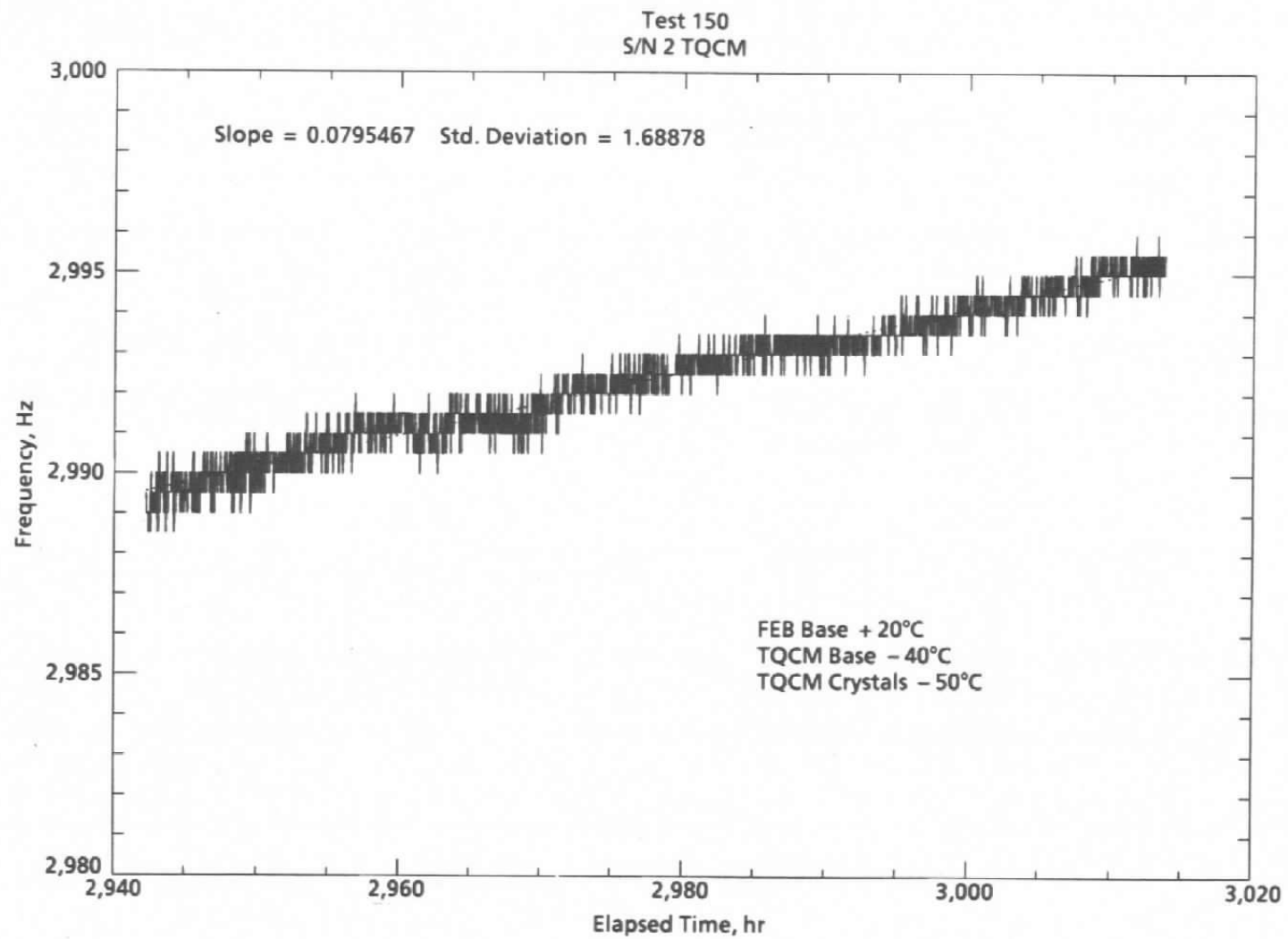


Figure 19. Variation of temperatures during 21-day drift test.

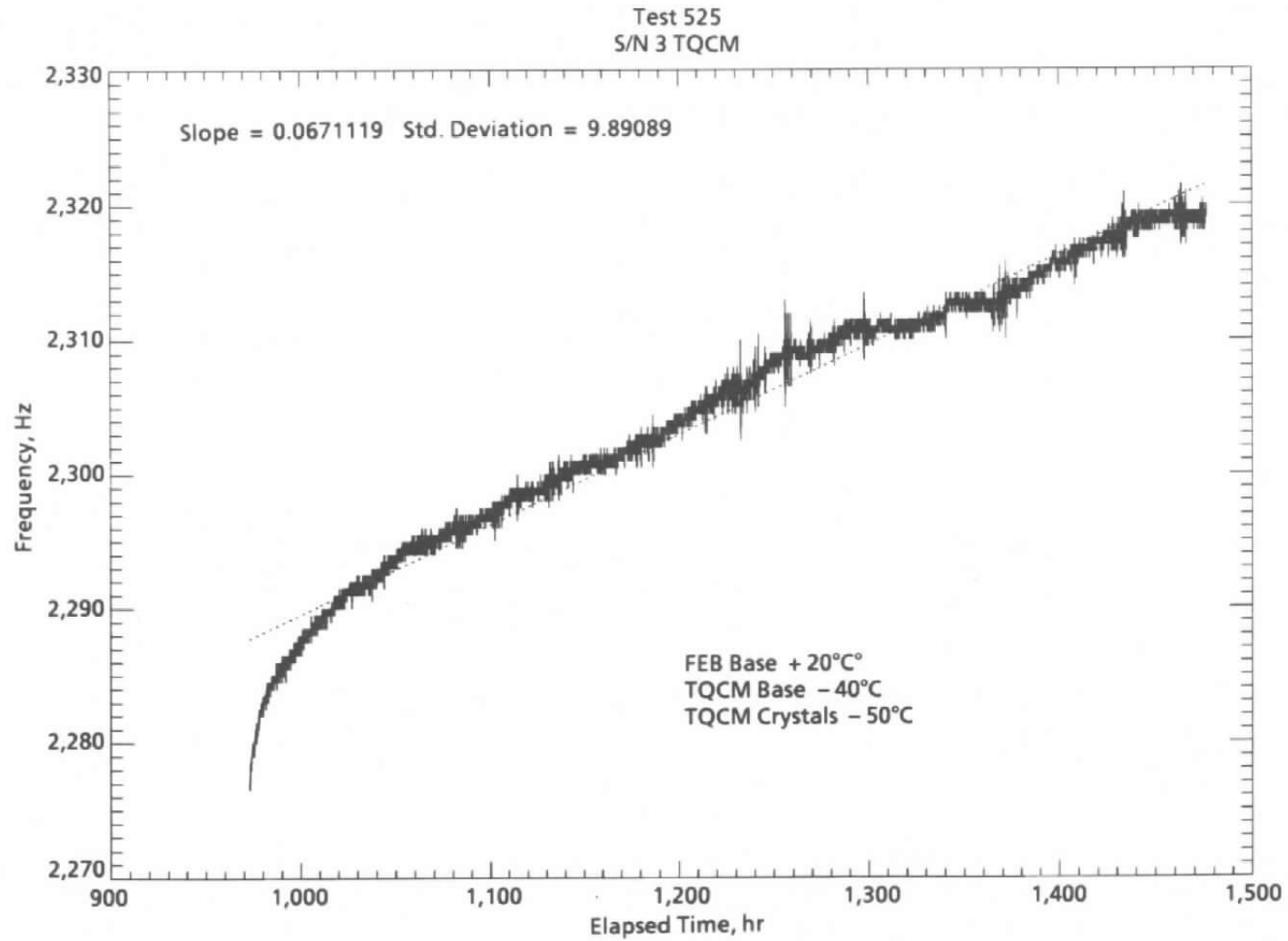


a. TQCM S/N 1 (21-day test)

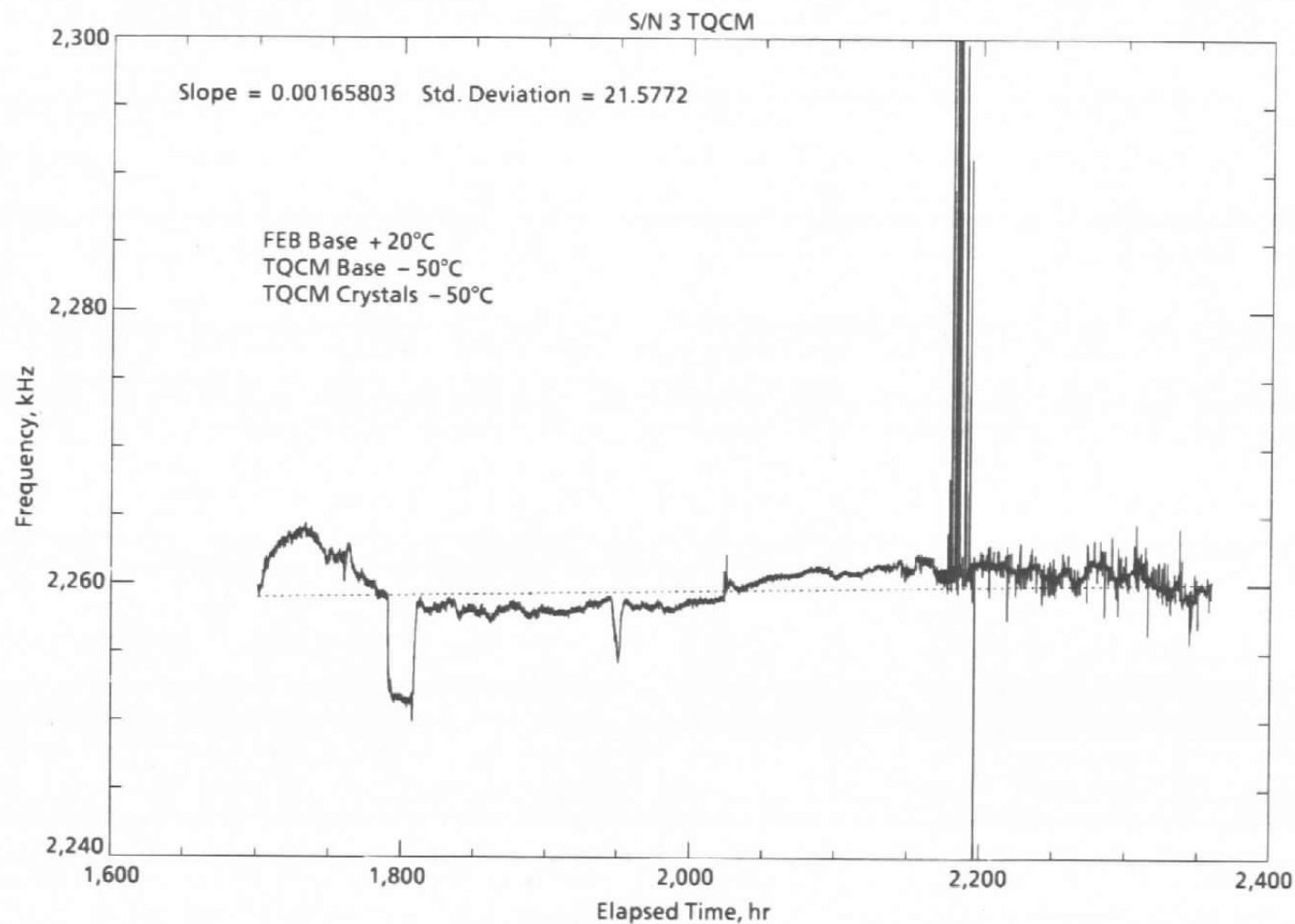
Figure 20. Variation of frequencies during drift tests.



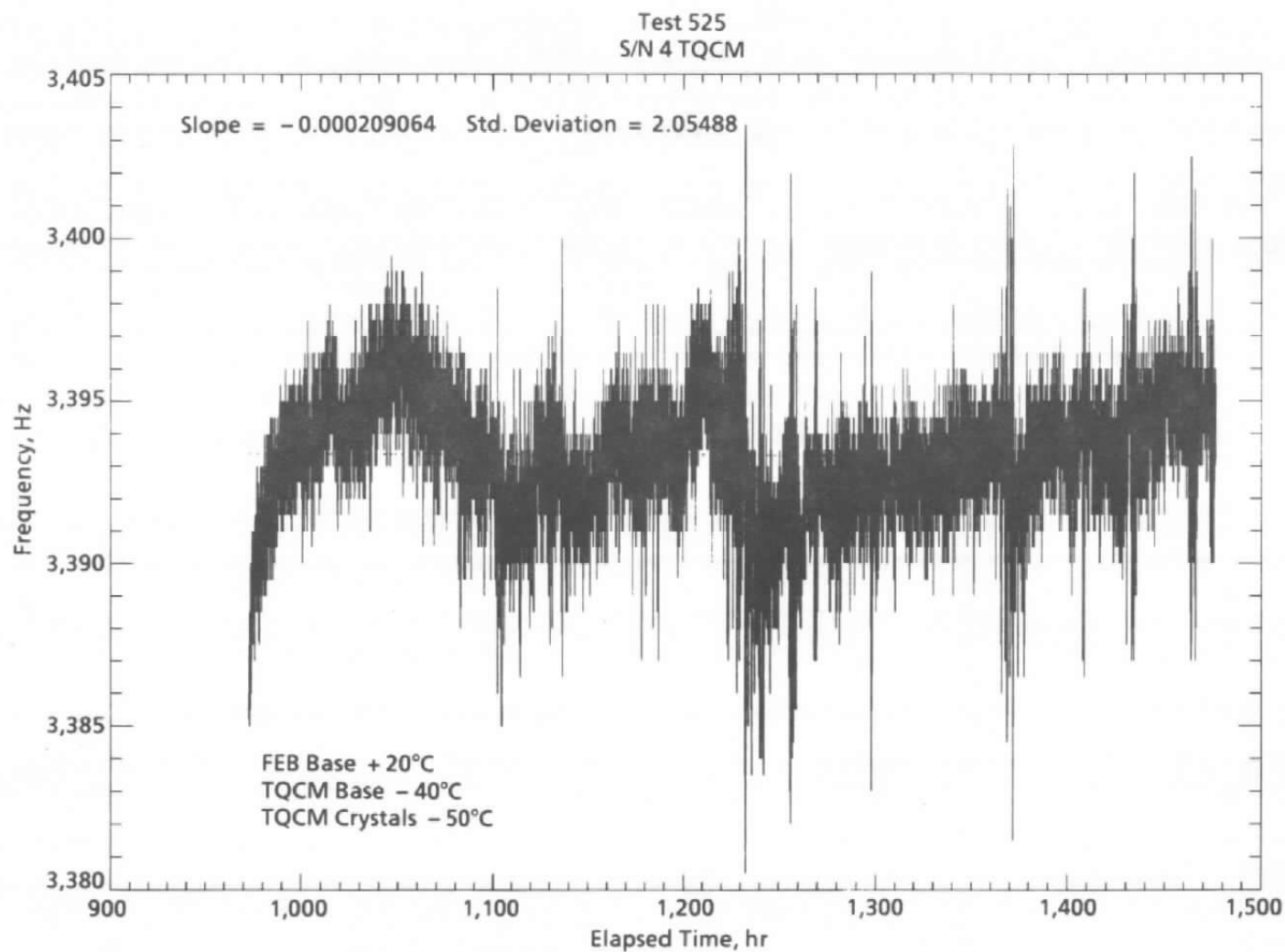
b. TQCM S/N 2 (3-day test)  
Figure 20. Continued.



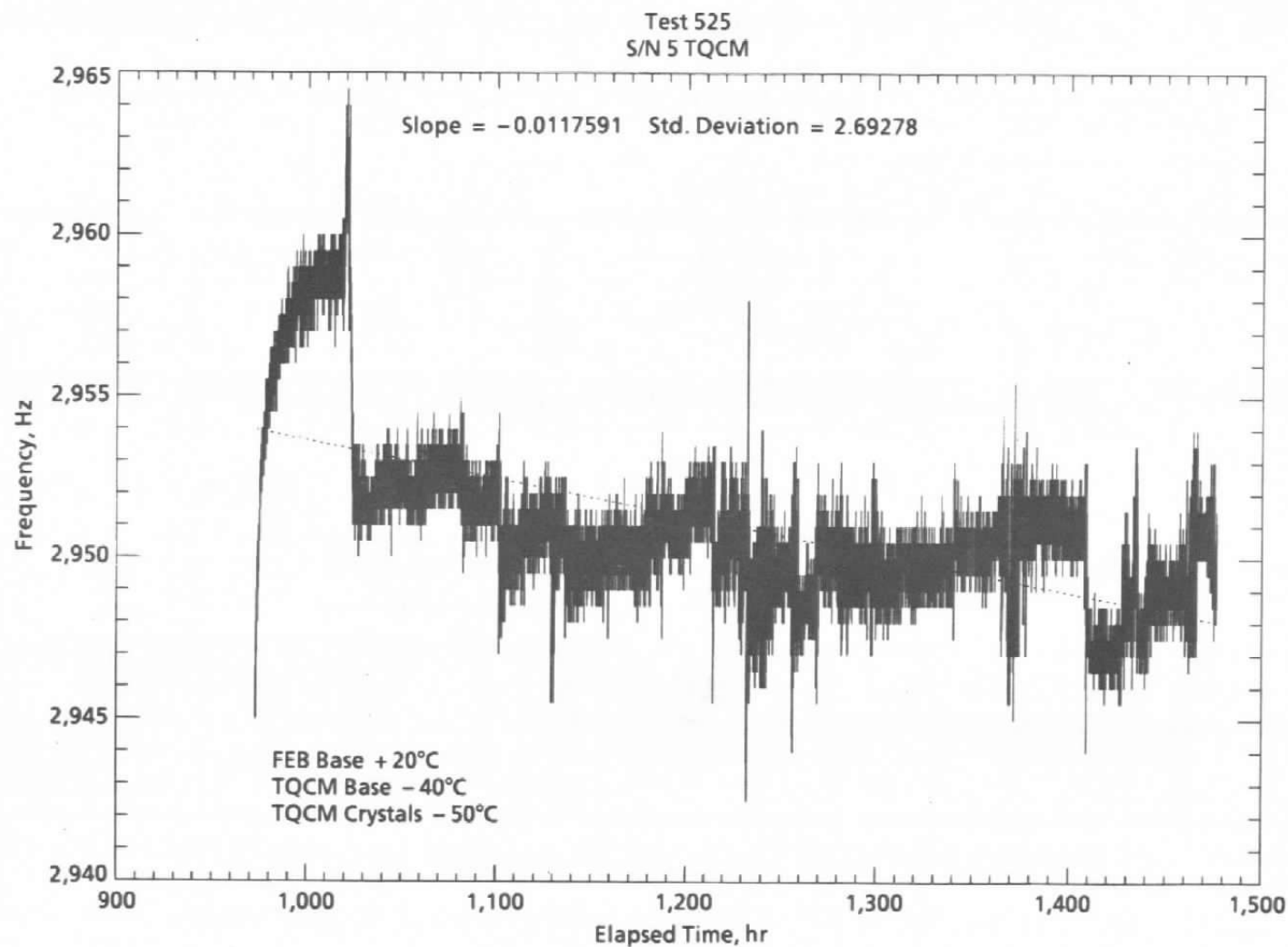
c. TQCM S/N 3 (21-day test)  
Figure 20. Continued.



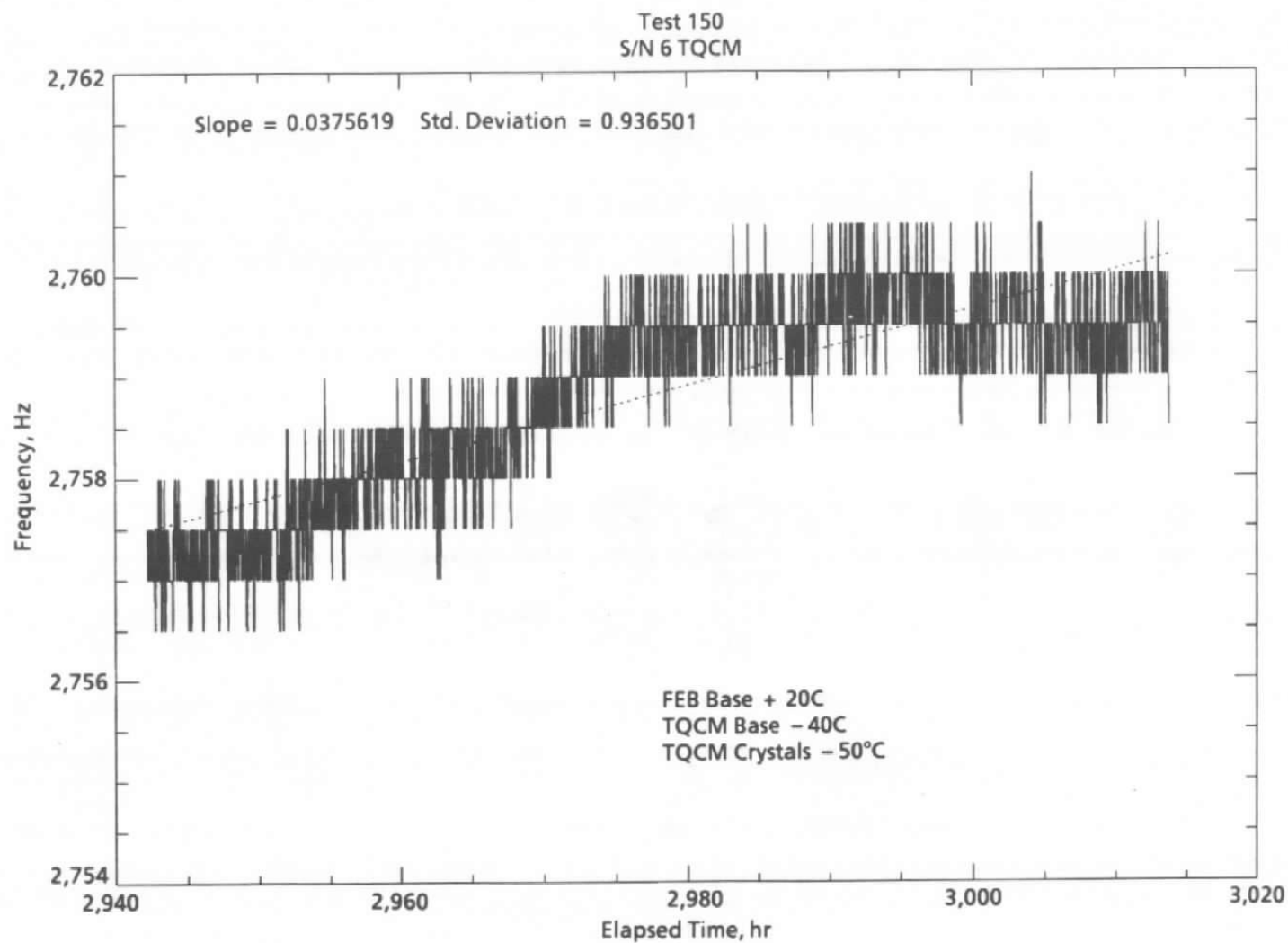
d. TQCM S/N 3 (28-day test)  
Figure 20. Continued.



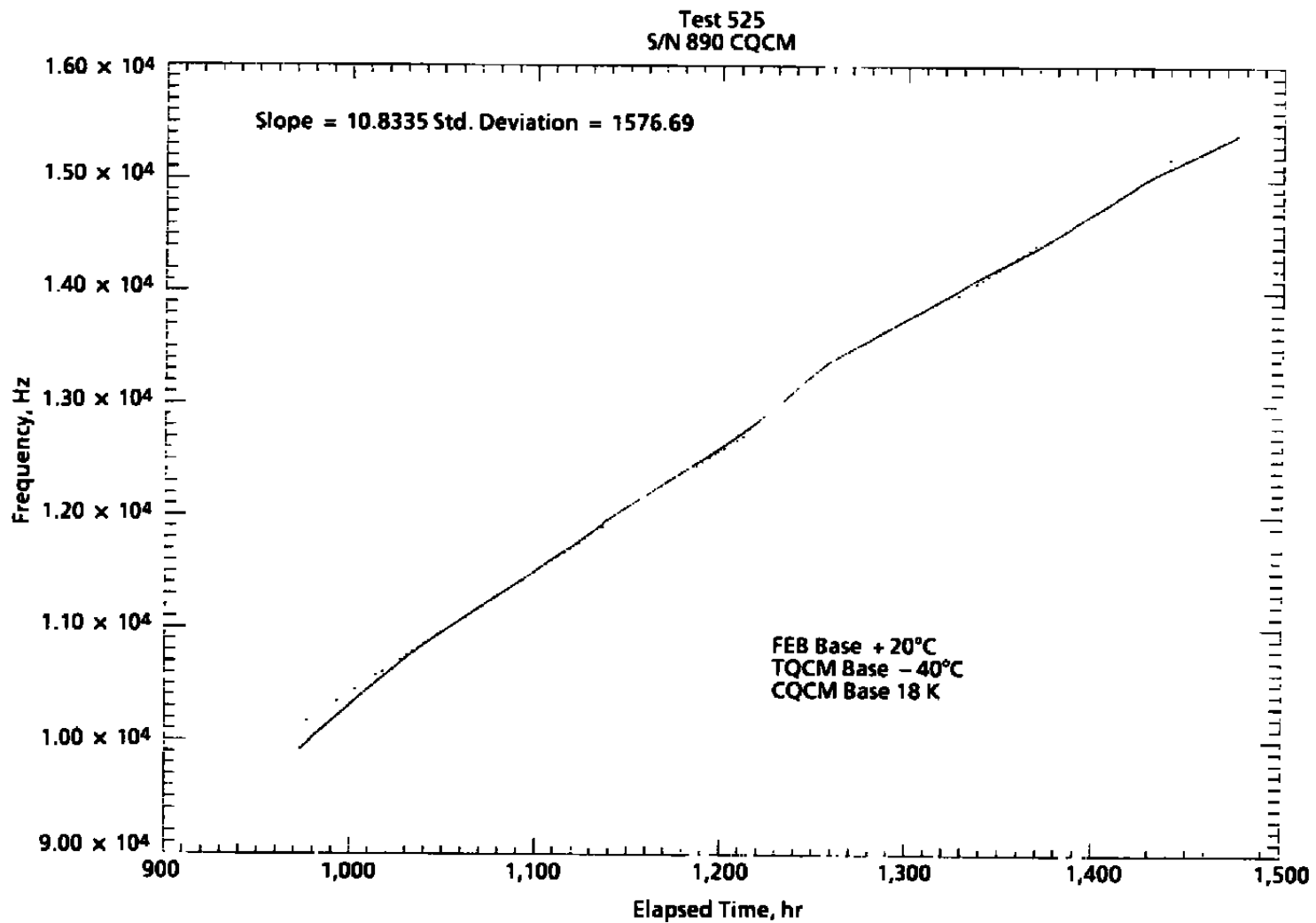
e. TQCM S/N 4 (21-day test)  
Figure 20. Continued.



f. TQCM S/N 5 (21-day test)  
Figure 20. Continued.



g. TQCM S/N 6 (3-day test)  
Figure 20. Continued.



**h. CQCM S/N 890 (21-day test)**  
**Figure 20. Concluded.**

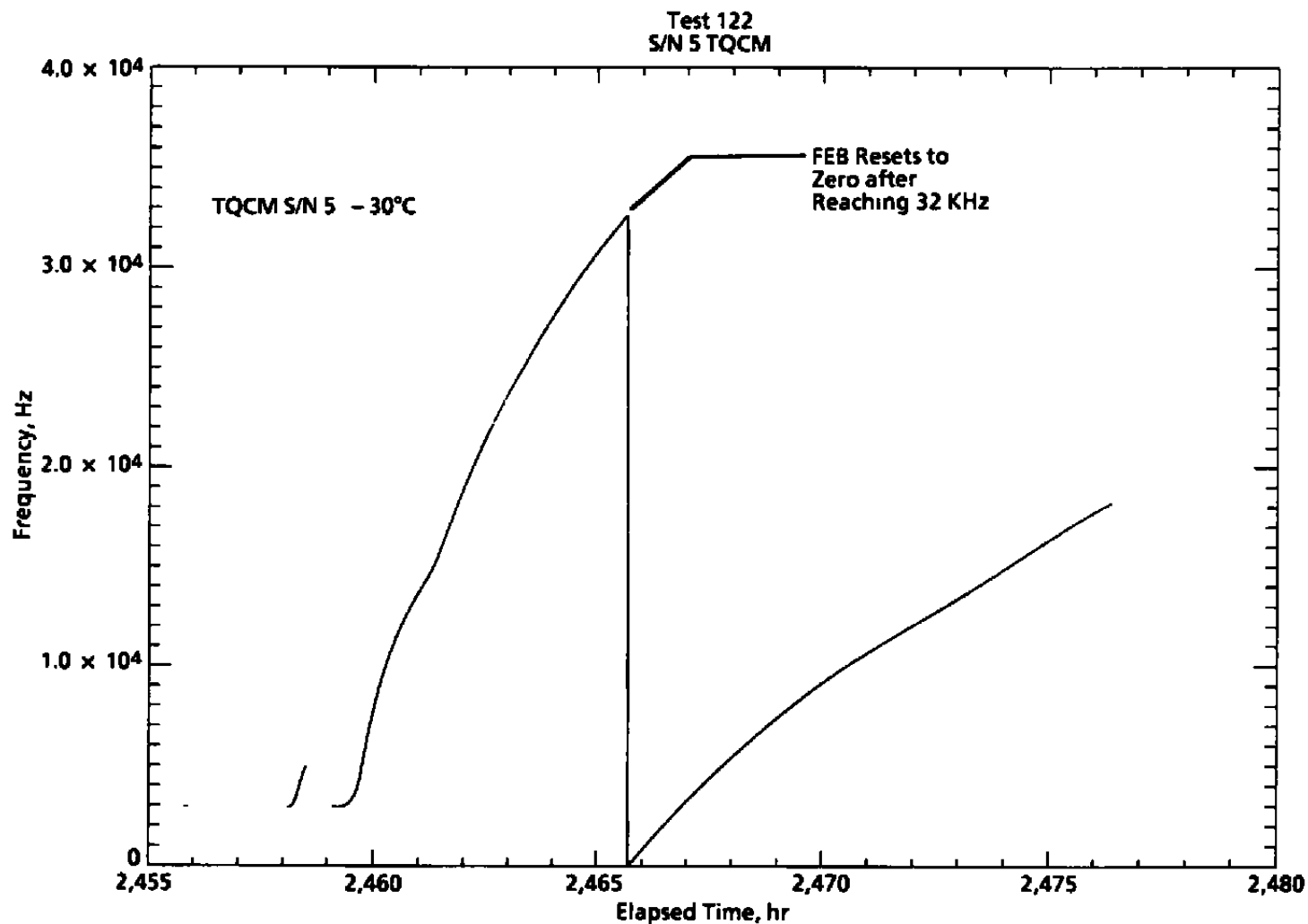


Figure 21. Material condensed on TQCM S/N 5 in upper chamber after FEB reinstalled in chamber.

Test 141  
S/N 5 TQCM

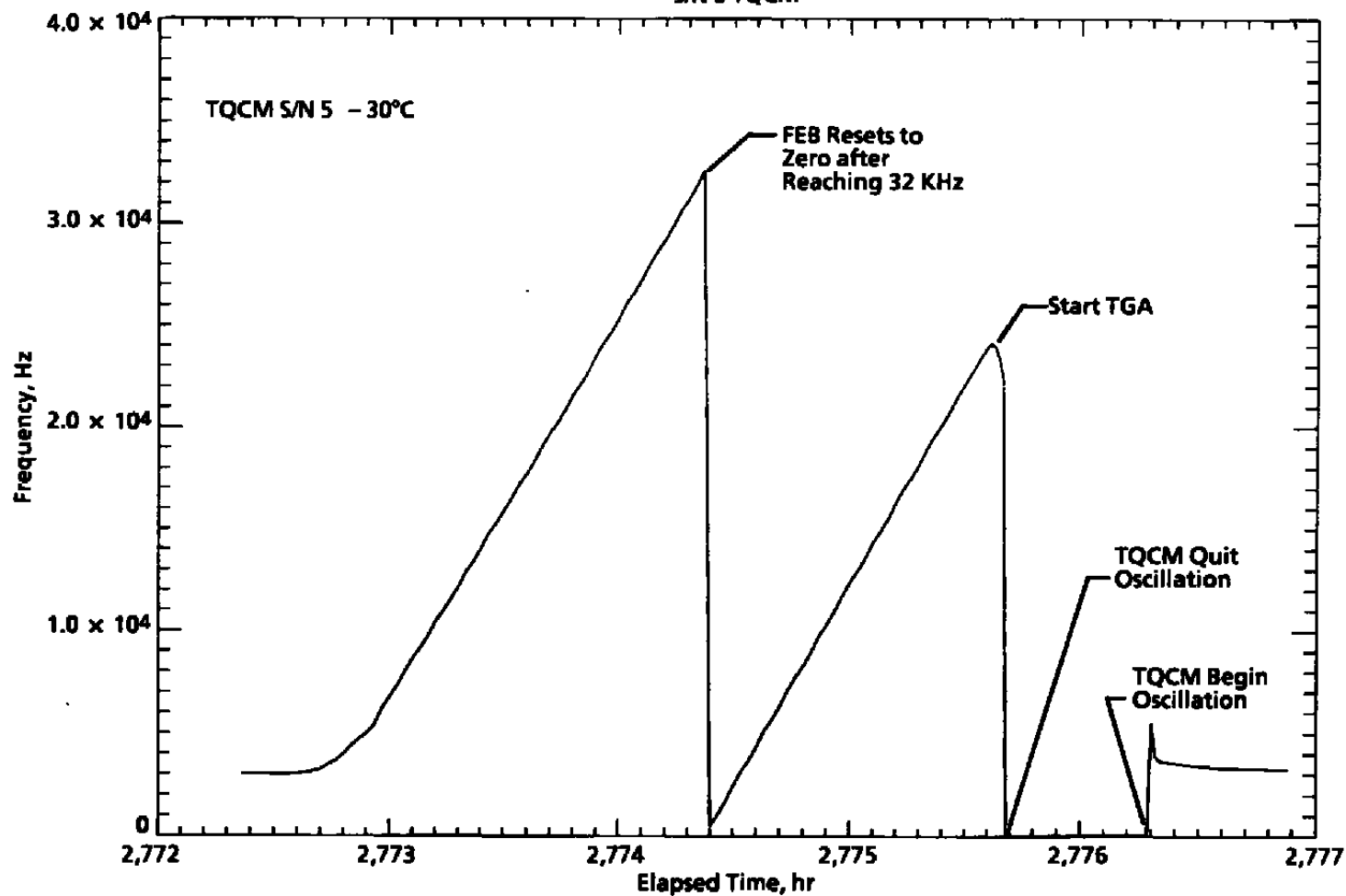


Figure 22. Material condensed on TQCM S/N 5 in upper chamber after FEB and flight cable reinstalled in chamber.

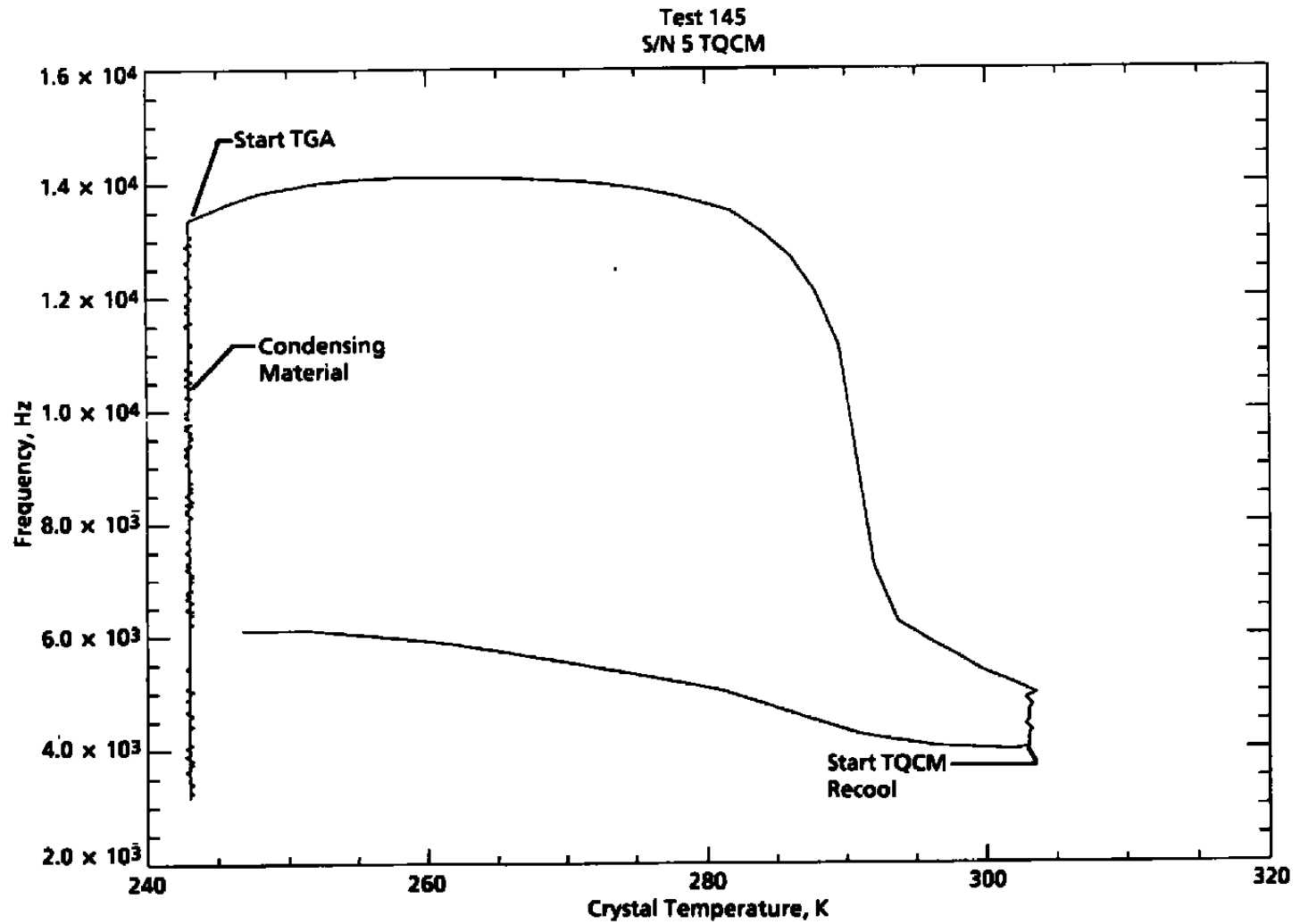


Figure 23. Material condensed on TQCM S/N5 in upper chamber after FEB and flight cable reinstalled in chamber and after 2 days of pumping — then TGA of material.

**Table 1. TQCM Configuration Versions**

<b>Configuration Version</b>	<b>TQCM Controlled By FEB (S/N)</b>	<b>TQCM Monitored by AEDC Instruments (S/N)</b>
<b>1</b>	<b>2, 3, 5, 6</b>	<b>1, 4</b>
<b>2</b>	<b>1, 3, 4, 5</b>	<b>None</b>
<b>3</b>	<b>None</b>	<b>3, 4</b>
<b>4</b>	<b>2, 3, 5*, 6</b>	<b>4</b>
<b>5</b>	<b>2, 3, 5*, 6</b>	<b>4</b>

\* TQCM S/N 5 mounted in upper chamber viewing FEB and cable.

Table 2. Plot File Catalog

IDL Test No.	QCM Start File	QCM End File	TQCM Placement Version	Date QCM Data Obtained	IDL Label File	Notes
100	T001F017	T001F018	Version 1	12/21/92	MSXLAB11	Initial pumpdown. Had a large amount of outgassing. Cooled S/N 2, 3, 5, 6 TQCM crystals to $-10^{\circ}\text{C}$ and picked up outgassing contaminant. Did TGA to $35^{\circ}\text{C}$ . Cryopump not on.
101	T001F022	T001F023	"	12/22/92	"	Cryopump turned on. FEB base $-29^{\circ}\text{C}$ ; TQCM base $-198^{\circ}\text{C}$ ; no control of crystal temperatures. First $\text{CO}_2$ deposit and TGA. Got too much $\text{CO}_2$ at first, so heated back up and redid.
102	T001F023	T001F023	"	12/22/92	"	TGA of second $\text{CO}_2$ deposit in Test 101 above.
201	T002F009	T002F010	"	1/9/93	"	FEB base $-29^{\circ}\text{C}$ , TQCM base $-195^{\circ}\text{C}$ ; power to FEB cycled off and on at 5-min intervals (TQCM-base temp. actually went down to 67 K before turned on the control circuit).
202	T002F011	T002F012	"	1/9/93	"	FEB base $-29^{\circ}\text{C}$ ; TQCM base start at $-195^{\circ}\text{C}$ . Add $\text{CO}_2$ and then do TGA—had to do TGA with the TQCM base because Peltier units did not work (except for S/N 5).
203	T002F018	T002F018	"	1/11/93	"	FEB base $-29^{\circ}\text{C}$ ; TQCM base $-90^{\circ}\text{C}$ . Cycle power to FEB on and off at 5-min intervals.
204	T002F019	T002F021	"	1/11/93	"	FEB base $-34^{\circ}\text{C}$ ; TQCM base $-195^{\circ}\text{C}$ . 4-hr cold soak and then recycled power to FEB off and on at 5-min intervals. Did Peltier check — only S/N 5 worked at this temperature.
205	T002F025	T002F026	"	1/12/93	"	FEB base $66^{\circ}\text{C}$ ; TQCM base $45^{\circ}\text{C}$ . 4-hr soak at this temperature and then cycled power to FEB off and on at 10-min intervals. Did Peltier check here and all worked.
206	T002F028	T002F044	"	1/12/93 thru 1/15/93	"	Cycled temperatures of FEB base from $-29^{\circ}$ to $66^{\circ}\text{C}$ and TQCM base from $-90^{\circ}$ to $40^{\circ}\text{C}$ . Cycled bases 5 times and stayed at end points for 4 hr. No temperature control of the TQCM crystals.
207	T002F044	T002F046	"	1/15/93	"	FEB base $-29^{\circ}\text{C}$ ; TQCM base $-90^{\circ}\text{C}$ . After 4-hr soak, cycled power to FEB off and on at 15-min intervals. Did Peltier check and all worked.
208	T002F048	T002F050	"	1/15/93	"	FEB base ramped to $20^{\circ}\text{C}$ and TQCM base ramped to $-40^{\circ}\text{C}$ at start. Did TGA of CQCM at $2.5^{\circ}\text{C}/\text{min}$ .

Table 2. Continued

IDL Test No.	QCM Start File	QCM End File	TQCM Placement Version	Date QCM Data Obtained	IDL Label File	Notes
301	T003F001	T003F005	Version 1	1/18/93	MSXLAB11	FEB base 20°C; TQCM base -40°C; S/N 1, 4 TQCM crystals not controlled. Cycled S/N 2, 3, 5, 6 TQCM crystals 5 times from -70° to 60°C at 2.5 C/min. Stayed at end points for 15 min.
302	T003F006	T003F017	"	1/18/93	"	FEB base 20°C; TQCM base -40°C; S/N 1, 4 TQCM crystals not controlled. Cycled S/N 2, 3, 5, 6 TQCM crystals 5 times from -70° to 60°C at 0.8°C/min. Stayed at end points for 15 min for first 2 cycles and for 25 min for the last 3 cycles.
401	T004F001	T004F007	"	1/21/93 thru 1/22/93	"	FEB base 20°C; S/N 1, 4 TQCM crystals not controlled. TQCM base cycled 1 time from -60 to -10°C at ~1°C/min at each of S/N 2, 3, 5, 6 crystal temperatures of -60°, -50°, -40°, -25°, 0°, and 60°C. Stayed at end points for 15 min.
601	T006F001	T006F012	"	1/22/93 thru 1/23/93	"	FEB base 20°C; TQCM base -40°C; S/N 1, 4 TQCM crystals not controlled. Cycled S/N 2, 3, 5, 6 TQCM crystals 3 times from -70° to 60°C at 0.8°C/min. Stayed at end points for 2 hr. S/N 2 TQCM Peltier unit quit working.
602	T006F012	T006F018	"	1/23/93 thru 1/24/93	"	FEB base 20°C; TQCM base -40°C; S/N 1, 4 TQCM crystals not controlled. Cycled S/N 2, 3, 5, 6 TQCM crystals 1 time from -70° to 60°C at 0.2°C/min. Stayed at end points for 2 hr.
603	T006F031	T006F034	"	1/25/93	"	FEB base 20°C; TQCM base -40°C. Did TGA of CQCM at 2.5°C/min.
604	T006F035	T006F040	"	1/25/93	"	FEB base 20°C; TQCM base -40°C. Cooled CQCM, then did TGA at 2.5°C/min; then cooled again.
701	T007F001	T007F006	"	1/25/93 thru 1/26/93	"	FEB base 20°C; S/N 1, 4 TQCM crystals not controlled. Cycled S/N 2, 3, 5, 6 TQCM crystals 1 time from -70° to 60°C at 2.5°C/min and CQCM crystal 1 time from 15 to 320 K at 5°C/min for each TQCM base temperature of -25°, 0°, 25°C. Stayed at end points for 30 min.
710	T006F037	T006F039	"	1/25/93	"	FEB base 20°C; TQCM base -40°C; TQCM crystals -70°C. Heat CQCM crystal from 17 to 320 K at 2.5°C/min.
711	T007F008	T007F008	"	1/26/93	"	FEB base 20°C; TQCM base -40°C; TQCM crystals -40°C. Heat CQCM crystal from 17 to 320 K at 10°C/min.

Table 2. Continued

IDL Test No.	QCM Start File	QCM End File	TQCM Placement Version	Date QCM Data Obtained	IDL Label File	Notes
712	T007F009	T007F010	Version 1	1/26/93	MSXLAB11	FEB base 20°C; TQCM base -40°C; TQM crystals -40°C Heat CQCM crystal from 17 to 320 K at 15°C/Min.
713	T007F011	T007F011	"	1/26/93	"	FEB base 20°C; (Switched FEB plate cooling over from LN <sub>2</sub> to plant water supply); TQCM base -40°C; TQCM crystals -40°C. Heat CQCM crystal from 17 to 320 K at 20°C/min.
714	T007F015	T007F015	"	1/27/93	"	FEB base 20°C; TQCM base 0°C; TQCM crystals -10°C. Heat CQCM crystal from 17 to 190 K at 10°C/min and then from 190 to 320 K at 2.5°C/min.
715	T007F017	T007F018	"	1/27/93	"	FEB base 20°C; TQCM base 0°C; TQCM crystals -10°C. Heat CQCM crystal from 17 to 190 K at 2.5°C/min and then from 190 to 320 K at 10°C/min.
901	T009F007	T009F008	Version 2	2/3/93	MSXLAB22	FEB plate 20°C; TQCM base -40°C. Did TGA of CQCM from 17 to 50 K at 1°C/min, then from 50 to 170 K at 5°C/min, and then from 170 to 320 K at 10°C/min.
902	T009F015	T009F023	"	2/4/93 thru 2/5/93	"	FEB plate 20°C; TQCM base -40°C. Cycled S/N 1, 3, 4, 5, TQCM crystals 5 times from -70° to 60°C at 2.5°C/min. Stayed at end points for 1 hr.
903	T009F023	T009F040	"	2/5/93 thru 2/7/93	"	FEB plate 20°C; TQCM plate -40°C. Cycled S/N 1, 3, 4, 5 TQCM crystals 5 times from -70° to 60°C at 0.8°C/min. Stayed at end points for 1 hr.
904	T009F042	T009F053	"	2/7/93 thru 2/8/93	"	FEB plate 20°C. Cycled S/N 1, 3, 4, 5 TQCM crystals 2 times from -70° to 60°C at 2.5°C/min for each TQCM plate temperature of -25°, 0°, and 25°C. Stayed at end points for 1 hr.
905	T009F054	T009F070	"	2/8/93 thru 2/10/93	"	FEB plate 20°C. Cycled TQCM base 1 time from -60° to -10°C at ~1.0°C/min for each S/N 1, 3, 4, 5 TQCM crystal temperature of -60°, -50°, -40°, -25°, 0°, and 60°C. Stayed at end points for 1 hr. This cycle test consists of two parts because of a computer problem — QCM files 54-57 and 62-70.
501	T005F001	T005F002	"	2/10/93	"	FEB base 20°C; TQCM base -40°C. Cycled power to FEB off and on at 10-min intervals. Peltiers on for first 2 cycles and off for second 2.

Table 2. Continued

IDL Test No.	QCM Start File	QCM End File	IQCM Placement Version	Date QCM Data Obtained	IDL Label File	Notes
525	T005F003	T005F128	Version 2	2/10/93 thru 3/3/93	MSXLAB22	FEB base 20°C; TQCM base - 40°C; S/N 1, 3, 4, 5 TQCM crystals - 50°C 21-day drift test. Data points were taken at 3-min intervals. (Had some large room temperature swings during test).
531	T005F128	T005F137	"	3/3/93 thru 3/4/93	"	FEB base 20°C; TQCM base - 40°C. S/N 1, 3, 4, 5 TQCM crystals cycled - 50° to 60°C at 1°C/min. Stayed at end points for 2 hr. (First heat cycle same as TGA after drift test).
532	T005F138	T005F145	"	3/4/93	"	FEB base 20°C; TQCM base - 40°C. Did TGA of CQCM at 1°C/min after drift test.
533	T005F146	T005F148	"	3/4/93	"	FEB base 20°C; TQCM base - 40°C. Did second TGA of CQCM at 1°C/min immediately after Test 532 above.
534	T005F152	T005F162	"	3/5/93 thru 3/6/93	"	FEB plate 20°C; S/N 1, 3, 4, 5 TQCM crystals - 50°C. Stepped TQCM base temperature - 40°, - 30°, - 20°, - 10°, 0°, 20°C. Stayed at each base temperature for 4 hr.
570	T005F017	T005F128	"	Same as Test 525	"	Same test as drift test (Test 525) above. First 14 files of test removed.
115	T011F004	T011F142	Version 3	3/12/93 thru 4/9/93	MSXLAB50	TQCM base - 50°C. Mini-drift test with TQCMs S/N 3 and S/N 4 and CQCM connected to AEDC instrumentation. (S/N 5 still mounted to TQCM base but not connected) FEB and S/N 1 TQCM removed from chamber for this test. CQCM crystal temperature remained at 293 K for early part of test.
116	T011F143	T011F145	"	4/9/93	"	TQCM base - 50°C. Did TGA of CQCM at 2.5°C/min after mini-drift test. (Using the 1819 CQCM controller).
122	T012F001	T012F008	Version 4	4/13/93 thru 4/14/93	MSXLAB33	FEB reinstalled after repair. S/N 5 TQCM mounted in top chamber to view the FEB and flight cables. Temperature sensor attached to S/N 3 TQCM mounting flange. Pumpdown and cool S/N 5 to - 30°C, then heating of FEB plate to 50°C. Cryopump start.
125	T012F010	T012F021	"	4/14/93 thru 4/15/93	"	FEB base 50°C; TQCM base - 40°C; S/N 5 TQCM crystal - 30°C (S/N 5 only controlled to - 22°C before cycle program reset); S/N 4 TQCM crystal not controlled. Cycled S/N 2, 3, 6 TQCM crystals 5 times from - 70° to 60°C at 2.5°C/min. Stayed at end points for 2 hr. Also did TGA of S/N 5 TQCM at 1°C/min and CQCM at 2.5°C/min during cycles. S/N 5 quit during TGA.

Table 2. Continued

IDL Test No.	QCM Start File	QCM End File	TQCM Placement Version	Date QCM Data Obtained	IDL Label File	Notes
141	T014F001	T014F004	Version 5	4/26/93	MSXLAB44	FEB and flight cable reinstalled after trip to Utah. S/N 5 TQCM mounted in top chamber to view the FEB and flight cables. Temperature sensor attached to S/N 3 TQCM mounting flange. Pumped down and set S/N 5 TQCM crystal to $-30^{\circ}\text{C}$ — picked up a large amount of deposit. Chamber pressure shows large amount of outgassing. Did TGA of S/N 5 at $1^{\circ}\text{C}/\text{min}$ — oscillation ceased. (Cryopump not on).
142	T014F009	T014F011	"	4/27/93	"	Did back-to-back TGAs of S/N 5 TQCM from $-30^{\circ}$ to $30^{\circ}\text{C}$ at $1^{\circ}\text{C}/\text{min}$ . In both cases, continued to pick up deposit while crystal temperature increased until reached $-4^{\circ}\text{C}$ . At that point, deposit started leaving. Chamber pressure still high. (Cryopump not on).
143	T014F012	T014F020	"	4/27/93 thru 4/28/93	"	S/N 5 TQCM crystal temperature $-30^{\circ}\text{C}$ . Heated FEB base to $50^{\circ}\text{C}$ — then started cryopump. Problem with CQCM base temperature sensor. Set TQCM base temperature controller to $-40^{\circ}\text{C}$ . Left running overnight — S/N 5 quit oscillating from apparent overload. Chamber pressure still high but better in a.m.
144	T014F021	T014F024	"	4/28/93	"	FEB base $50^{\circ}\text{C}$ ; TQCM base $-40^{\circ}\text{C}$ . Did TGA of S/N 5 TQCM from $-30^{\circ}$ to $30^{\circ}\text{C}$ at $2.5^{\circ}\text{C}/\text{min}$ — oscillator restarted at about $23^{\circ}\text{C}$ . Did TGA of CQCM from 19 to 320 K at $2.5^{\circ}\text{C}/\text{min}$ .
145	T014F025	T014F030	Version 5	4/28/93 thru 4/29/93	MSXLAB44	FEB plate $50^{\circ}\text{C}$ ; TQCM base $-40^{\circ}\text{C}$ . Pumped on chamber during day and overnight. Pressure lower in a.m. and the deposit rate on S/N 5 much lower. Did TGA on S/N 5 TQCM from $-30^{\circ}$ to $30^{\circ}\text{C}$ at $1^{\circ}\text{C}/\text{min}$ and on CQCM from 19 to 320 K at $2.5^{\circ}\text{C}/\text{min}$ .
146	T014F031	T014F040	"	4/29/93 thru 4/30/93	"	TQCM base $-40^{\circ}\text{C}$ ; S/N 2, 3, 6 TQCM crystals $50^{\circ}\text{C}$ ; S/N 5 TQCM crystal $-30^{\circ}\text{C}$ ; S/N 4 TQCM crystal not controlled. Cycled FEB base 3 times from $-25^{\circ}$ to $50^{\circ}\text{C}$ . Stayed at end points 2 hr.
147	T014F041	T014F048	"	4/30/93 thru 5/1/93	"	FEB base $50^{\circ}\text{C}$ ; TQCM base $-40^{\circ}\text{C}$ ; S/N 5 TQCM crystal $-30^{\circ}\text{C}$ . Cycled S/N 2, 3, 6 TQCM crystals 3 times from $-60^{\circ}$ to $60^{\circ}\text{C}$ at $2.5^{\circ}\text{C}/\text{min}$ . S/N 4 TQCM crystal not controlled. Stayed at end points for 2 hr.
148	T014F050	T014F057	"	5/1/93 thru 5/2/93	"	FEB base $20^{\circ}\text{C}$ ; TQCM base $-40^{\circ}\text{C}$ ; S/N 5 TQCM crystal $-30^{\circ}\text{C}$ . Cycled S/N 2, 3, 6 TQCM crystals 3 times from $-60^{\circ}$ to $60^{\circ}\text{C}$ at $2.5^{\circ}\text{C}/\text{min}$ . S/N 4 TQCM crystal not controlled. Stayed at end points for 2 hr.

**Table 2. Concluded**

IDL Test No.	QCM Start File	QCM End File	TQCM Placement Version	Date QCM Data Obtained	IDL Label File	Notes
149	T014F061	T014F068	Version 5	5/2/93 thru 5/3/93	MSXLAB44	FEB base 20°C; S/N 2, 3, 6 TQCM crystals – 50°C; S/N 5 TQCM crystal – 30°C; S/N 4 TQCM crystal not controlled. Cycled TQCM base 3 times from –60° to –10°C at ~1°C/min. Stayed at end points for 2 hr.
150	T014F070	T014F096	"	5/3/93 thru 5/6/93	"	FEB base 20°C (Switched FEB plate cooling over from LN <sub>2</sub> to plant water supply); TQCM base –40°C. S/N 5 TQCM crystal temperature ~ 30°C; S/N 4 TQCM not controlled; S/N 2, 3, 6 TQCMs crystal temperatures – 50°C. Did 3-day drift test.
151	T014F097	T014F097	"	5/6/93	"	FEB base 20°C; TQCM base –40°C. Did TGA of S/N 2, 3, 5, 6 TQCMs to 30° and then continued to 50°C at 2.5°C/min. Did TGA of CQCM to 320 K at 2.5°C/min.